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The University of Michigan
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ELECTROMECHANICAL

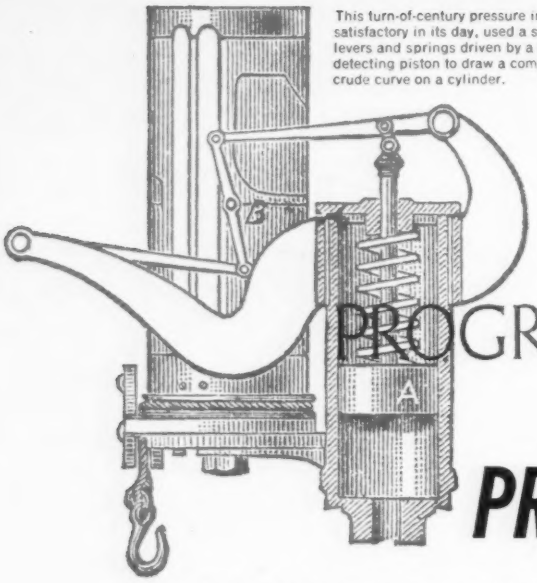
components & systems DESIGN

FEBRUARY 1959

In this issue

COMPONENTS DIGEST NO. 3

Electromagnetic and Potentiometer Transducers



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The Sourcebook of Design Ideas in Applied Electromechanics

VOL. 3, NO. 2

FEBRUARY 1959

ELECTROMECHANICAL components & systems DESIGN

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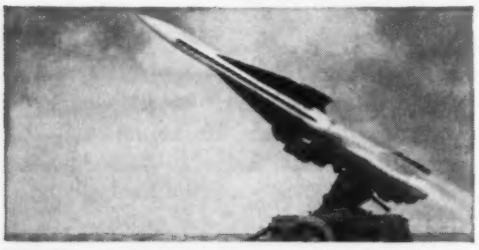
Raytheon Missile Projects

SPARROW III—the Navy's tenacious, lightning-fast, air-to-air missile—is intended for extensive use by Navy fighter aircraft in fleet air defense. Sparrow III is a Raytheon prime contract.



HAWK—the Army's defense against low-altitude attackers—carries out its destruction in the blind zone of conventional radars. Hawk development and production is under Raytheon prime contract.

TARTAR—A substantial contract for vital electronic controls for this Navy destroyer-launched missile is held by Raytheon. This equipment—a tracking radar and associated units—enables it to "lock on", cling to target's path, despite evasive tactics.

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SYSTEMS DIGESTS

Our recent emphasis on Components Digest supplements and reports of reader enthusiasm for this new series does not mean that we have altered our editorial objective—that we are reporting primarily to components designers. The editorial objective of this magazine is still, as it was at its inception, to function for you as a sourcebook of ideas and techniques in *all* areas of electromechanical research, development, design and the management of these functions. Our true emphasis is on designs and developments that culminate in actual working equipment, both systems and components, rather than on abstract mathematical systems.

Lines of distinction between components and systems are nebulous. Some of the series of supplements scheduled as Components Digests for future issues could as well be called Systems Digests. We have used the term components here in the broadest sense to mean any widely used module of equipment that has a definite name and a set of standards for judging it. As time goes on, the Digest's supplements will include more complex units of equipment, and when a reported equipment reaches some arbitrary degree of complexity we will call it a Systems Digest.

Moreover, we are confident that systems engineers will make wide use of these Digests. Probably the greatest weakness in many systems engineers is a lack of knowledge of components and system modules. Very often they specify transfer functions and frequency responses in their black boxes that don't correspond to the performance of any actual equipment. The more knowledge they have of the performance limitations of actual equipment, the less time they will spend in R and D trying to fulfill impossible specs.

TRANSDUCER PRESSURE

As originally scheduled, each Digest Supplement was to be limited to no more than 16 full pages. We find that adequate coverage of some subjects chosen cannot be so confined. The Components Digest subject for this issue, "Electromagnetic and Potentiometer Transducers" has a special diversity that forces its continuation in future issues. A second part of CD 3 covering widely-known commercial electromagnetic transducers will appear in the March Issue. A third, and final, part covering accelerometers, displacement and pressure transducers, performance data on typical transducers of each type and a buyers' guide will appear in the May Issue. However, this extension of CD 3 will not interfere with the schedule of future Digest Supplements as originally announced.

Robert B. Brotherston
Editor

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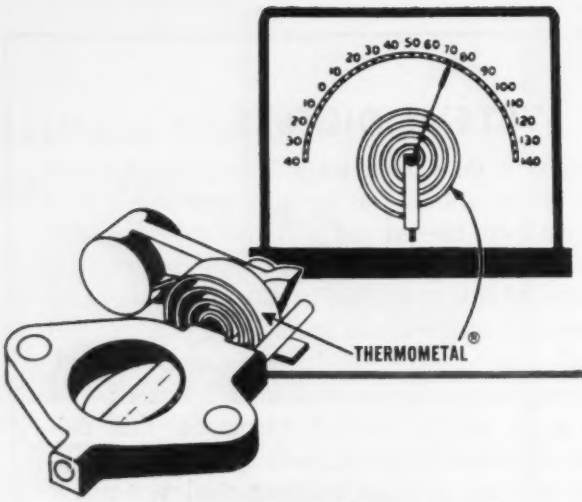

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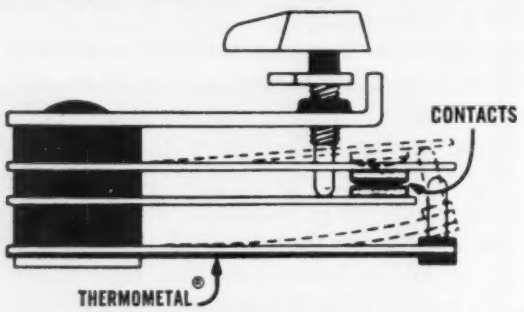

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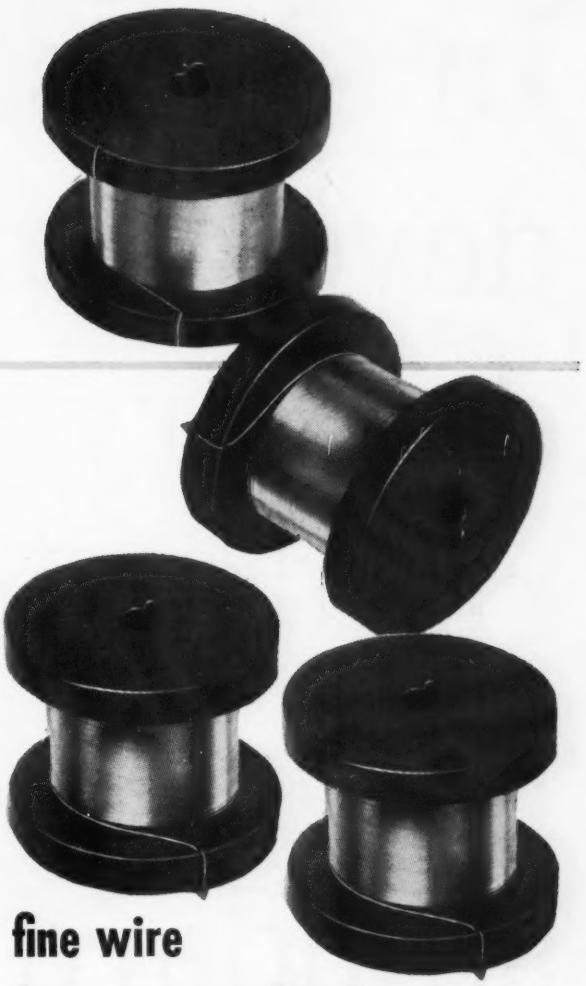

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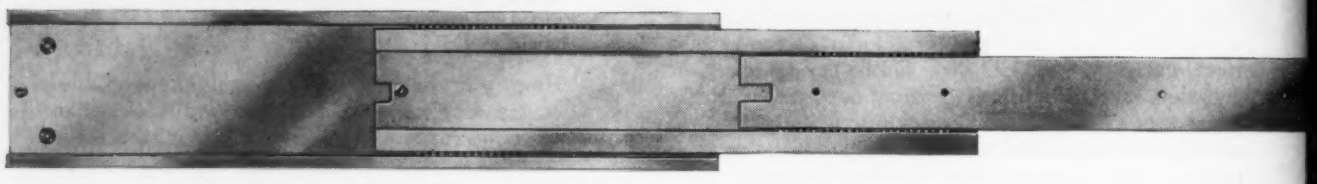

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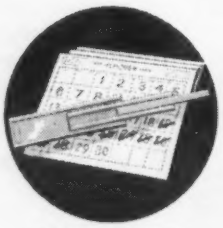

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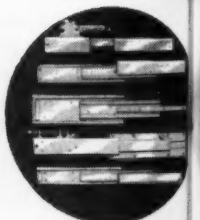

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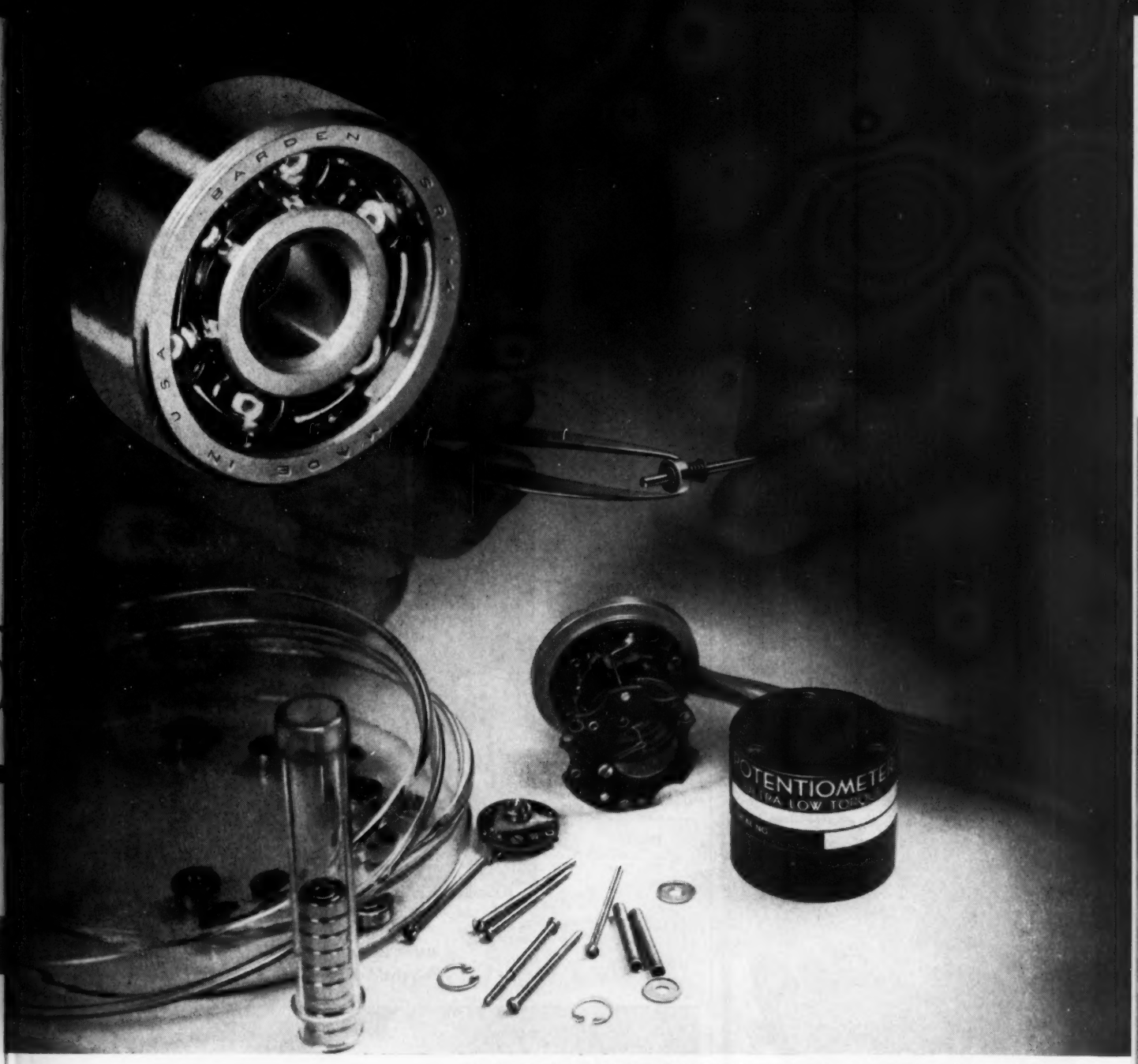

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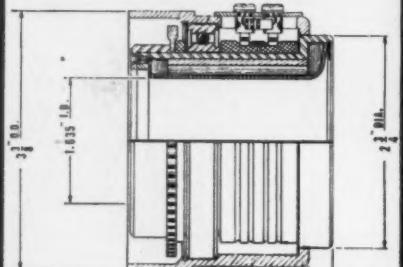

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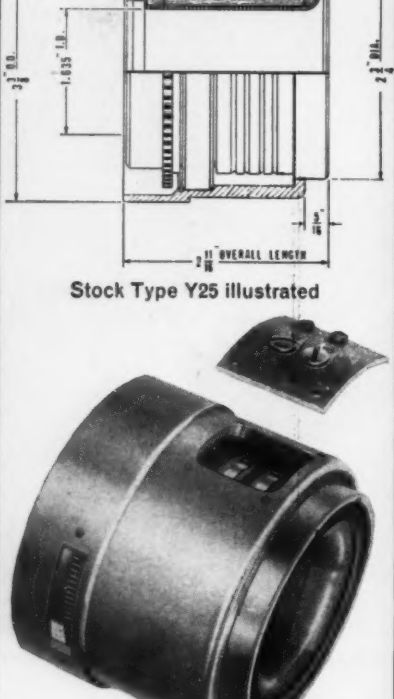

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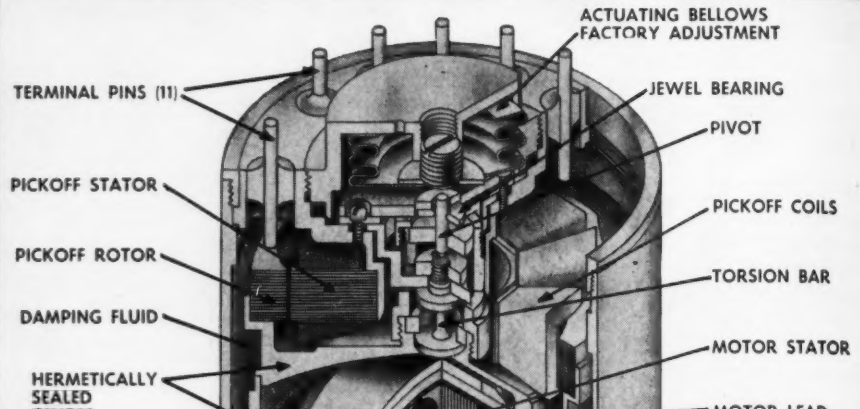
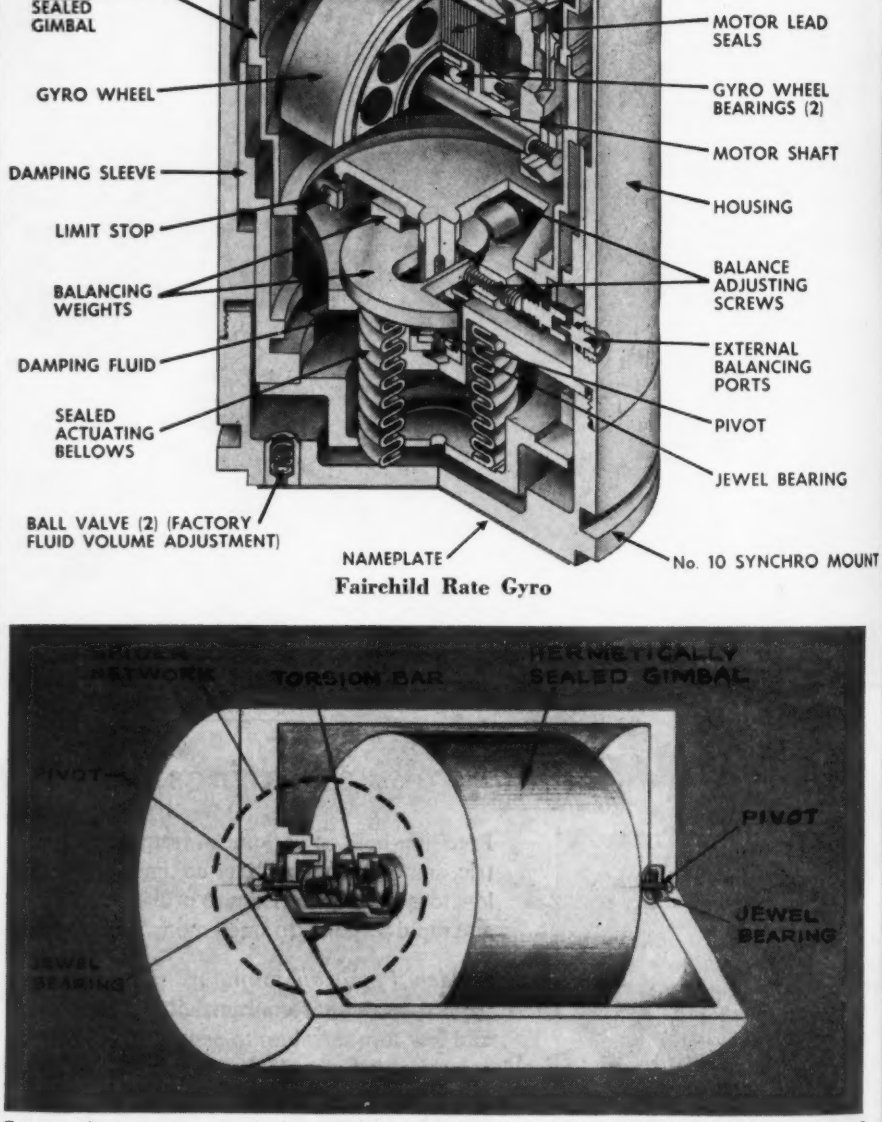


Fairchild Rate Gyro



Supporting structure of the RG-100 showing pivots and jewel bearings at both ends of the gimbal in line with the torsion bar. Use of a spider network, between the gimbal assembly and the pivots, circumvents the torsion bar and relieves it from the overtaxing responsibility (especially at low rates) of supporting the gimbal. The spider network offers no interference and permits the proper exertion of torque to the torsion bar from the gimbal assembly. The damping fluid also acts as a buffer for the entire gimbal mass thus reducing reaction to outside shock of the pivot against the jewel bearing, and since the torsion bar is capable of withstanding compression and tension forces, the gyro is protected against shocks and vibrations of high magnitude.

MINIATURE RATE GYRO

"Inside-Out" Differential Transformer Pickoff

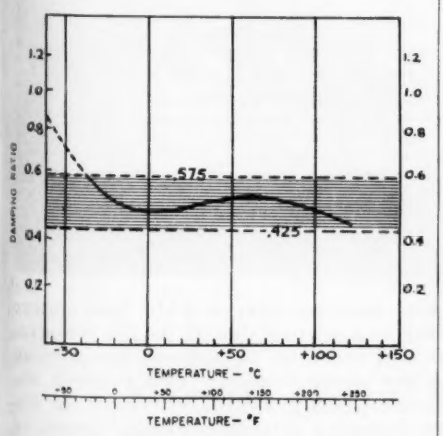
In designing a pickoff for a miniature precision gyro, engineers face a compromise among inherently incompatable design objectives. To achieve the best possible compromise in the pickoff for their RG-100 Rate Gyro, Fairchild Controls Corp. uses a differential transformer with unique construction. The rotor is designed around the stator, instead of inside it, as in conventional designs, to gain considerable advantage.

The twelve fingers of the stator readily accept machine wound coils. These coils, since they are wound, impregnated, and cured on a winding mandrel, can be wound with any size wire. Wire as small as #51 has been used successfully. The coils are wound to a form achieving maximum space efficiency.

A typical pickoff with a choke in series with the primary to correct the phase shift and excited with 400 cps power has the following characteristics:

Size—0.815dia x 0.250 thick
Sensitivity—6 volts at 2½°
Null—5 mv average
Phase shift—choke corrected
Stability—0.002%/°C
Linearity—0.1% of full scale to ½ scale
3.5% of full scale to full scale
Power—1.8 watts
Reliability—excellent

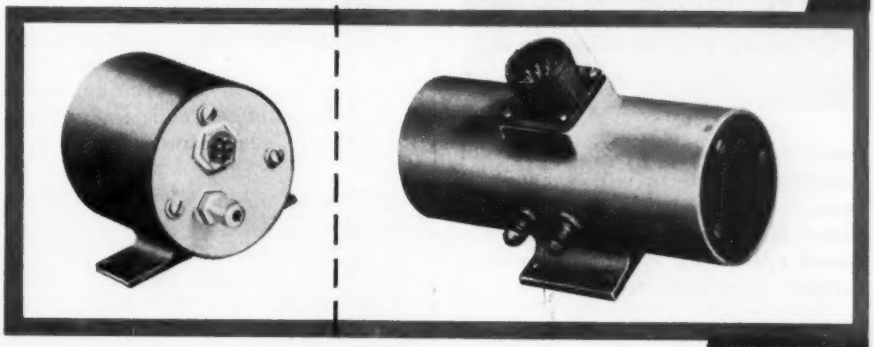
Using #51 wire, Fairchild has achieved sensitivity as high as 18 volts at 2½ degrees.



Typical damping curve for RG-100 Rate Gyro.

TIC OF CALIFORNIA

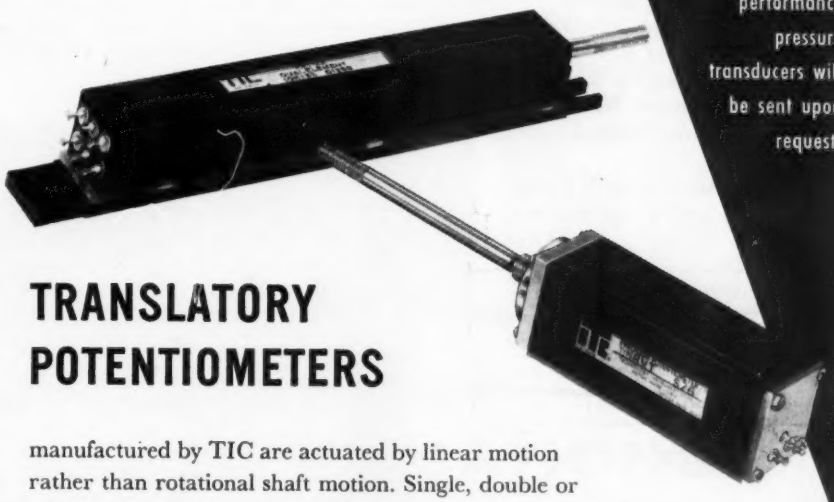
PRESSURE TRANSDUCERS



...measure absolute, gage or differential pressures.

Used to measure pressures in extreme environmental conditions with a high degree of accuracy, they are designed for use with non-corrosive fluids. Output is either one or two potentiometers whose functions are linear with pressure. Advanced techniques employ the TIC patented metal film type resistance elements providing infinite resolution and hermetic sealing to withstand critical environmental conditions. Deviations in external configuration can be made to meet individual requirements.

The TIC engineering staff is well qualified to design non-linear empirical functions which often occur in airborne systems. Descriptive literature on high performance pressure transducers will be sent upon request.



TRANSLATORY POTENTIOMETERS

manufactured by TIC are actuated by linear motion rather than rotational shaft motion. Single, double or triple resistance elements can be installed in the same unit. Stroke lengths of 2½", 5", 8", 12" and 15" are standard. Both linear and non-linear functions are available in either wirewound or the TIC patented metal film hermetic sealed encapsulated resistance element.

Full particulars will be sent upon request.

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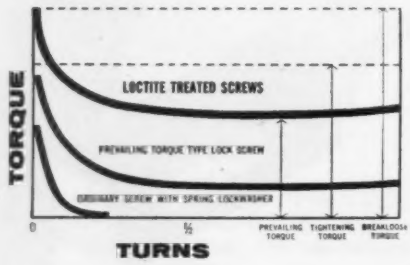
Insulating varnishes and mechanical punching have been widely used for years for the lack of a better method. Now there is a retaining compound designed specifically for thread locking. Consider these advantages:

1. LOCTITE provides complete resistance to loosening under shock or vibration because it fills and locks engaging threads, providing *both* breakloose and prevailing torque.
2. LOCTITE has several times the holding power of locknuts or lockscrews because locking action extends over entire engaged surface and persists for several turns.
3. LOCTITE is easy to apply . . . not sticky . . . no mess . . . does not air dry! Hardens only in absence of air. Large batches of threaded parts can be treated and stored for days . . . lock only when assembled. No heating or mixing is necessary.
4. LOCTITE comes in different strengths which apply any required locking torque—ranging from a light drag suitable for adjustment screws to a locking force exceeding the torsional strength of the screw. Provides greater uniformity than mechanical staking.

LOCKING CHARACTERISTICS OF LOCTITE



LOCTITE is a thin liquid that hardens when confined between closely fitting metal parts. It forms a tough, heat and oil-resistant, bond that secures threaded parts better than any mechanical locking device. Write for literature and free sample.

LOCTITE® SEALANT

AMERICAN SEALANTS COMPANY

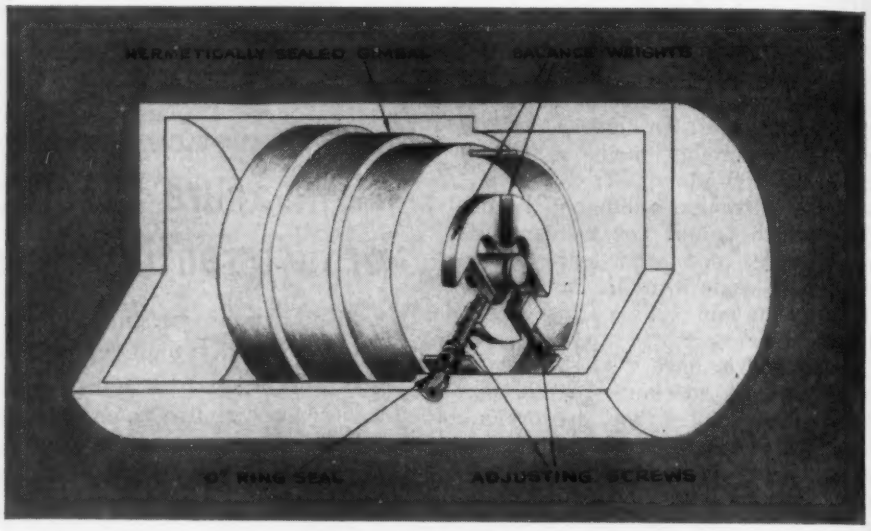
109 Woodbine St., Hartford 6, Conn.

In Canada: J. S. Parkes & Co., Ltd., Montreal

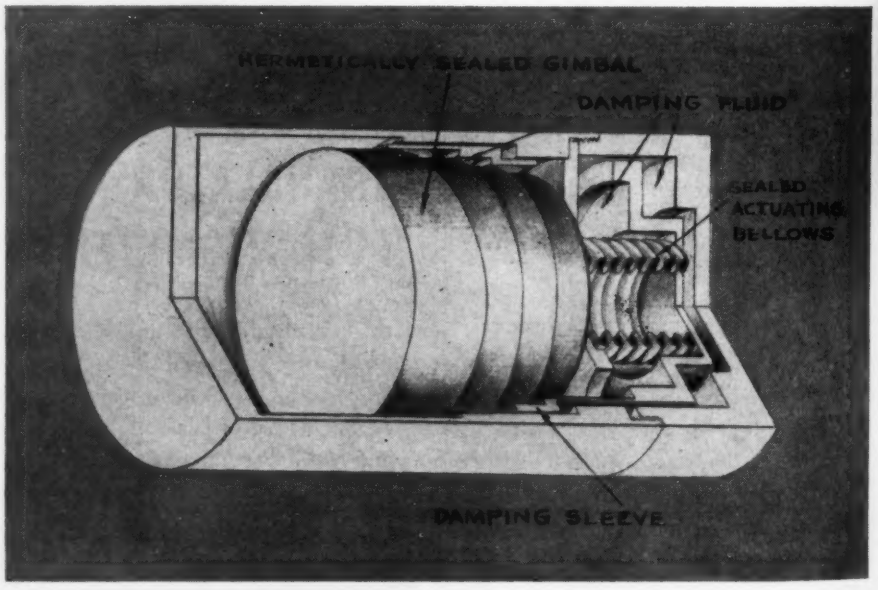
CIRCLE 7 ON INQUIRY CARD

In addition to its unique pickoff design, the RG-100 Rate Gyro, designed as a control and stabilization element for missile and aircraft applications, has other interesting characteristics contributing to high precision: external adjusting ports enable precise gimbal balance after assembly; a controlled damping mechanism affords uniform controlled damping over a wide temperature range without heaters, and pivots with jewel bearings support the gimbal at both ends relieving the torsion bar from this damaging responsibility. Due principally to use of these pivots, the RG-100 is capable of withstanding 100 G's of shock and 15 G's to 200 cps minimum vibration on any axis at rates even lower than 20°/sec.

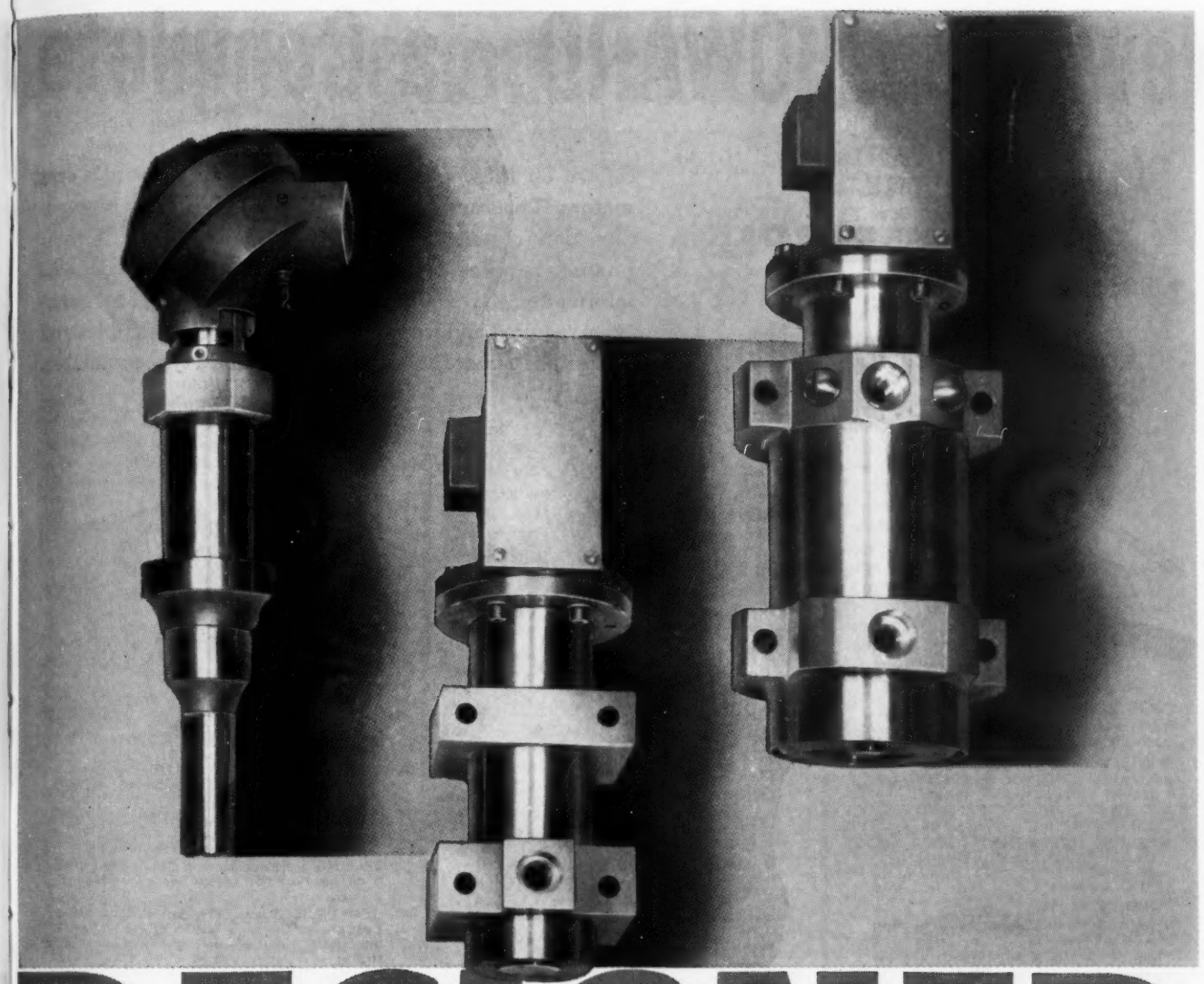
Circle No. 83 on Inquiry Card



External balance adjusting in the Fairchild Rate Gyro is accomplished during assembly by moving balance weights fixed to the gimbal through means of spade-like screws. The balance weights have elongated center holes to allow movement in one plane. Two balance weights are located back-to-back with the elongated holes 90° apart to permit adjustments in two planes. Final gimbal balance, therefore, can be made after assembly with less difficulty and greater accuracy insuring a more precise unit. After adjustment, the spade-like screws are left in a position within the slot of the adjusting screws so as to allow free movement of the gimbal.



Damping mechanism, to maintain uniform damping over a wide temperature range, uses damping medium (silicon fluid) as a sensing device. As the temperature rises, the fluid becomes less viscous and increases in volume compressing the sealed actuating bellows and causing the shear damping area between the damping sleeve and gimbal to be increased. The process is reversed as the temperature decreases. The damping area is varied systematically by means of the step construction between the gimbal and damping sleeve so as to insure a linear or uniform controlled damping throughout temperature range from —40°F to 200°F.



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SPECIFICALLY FOR NUCLEAR APPLICATIONS

These transducers are an engineered family of highly reliable instruments for measuring pressure temperature, flow, liquid level and differential pressure. » » Compact and rugged construction enables the units to meet the severe environmental conditions of MIL-N-19900 while maintaining outstanding accuracy. » » For any transducing application wherein reliability is a paramount consideration you should review the specification of these nuclear transducers. ***Consolidated Controls Corp.*** also designs and manufactures complete Instrumentation and Control Systems using static components. Complete details available by contacting Dept. NT.

CCc ***CONSOLIDATED CONTROLS CORP.***

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A SUBSIDIARY OF CONSOLIDATED DIESEL ELECTRIC CORPORATION,
STAMFORD, CONNECTICUT

CIRCLE 8 ON INQUIRY CARD

New from HOWARD...a Complete line

• UNIVERSAL

• SHADED POLE

• INDUCTION

Ratios from 3:1 to 2700:1

Shown on these pages are just a few of Howard's gear motors. Thousands of combinations and ratios are available in universal, shaded pole and induction types. If your product requires gear motors, check today for complete information. Give us details of your application and quantities required and we will be happy to submit samples and quotations or more information on standard types available.

SHADED POLE

MODEL 300

TYPE: Two Pole Shaded Pole AC—3200 R.P.M.

WIDTH: 2-15/32". LENGTH: 3-7/8".

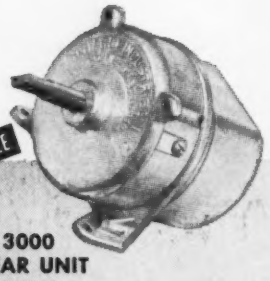
MAXIMUM CONTINUOUS TORQUE OZ. IN. (at 11/16" Stacking Length).
*1 R.P.M. 500 oz. in.
*150 R.P.M. 3.3 oz in.

MAXIMUM INTERMITTENT TORQUE OZ. IN. (at 11/16" Stacking Length).
*1 R.P.M. 750 oz in.
*150 R.P.M. 5 oz. in.

VOLTS: 12 to 115.

BEARINGS: Porous bronze sleeve bearing with oil reservoir.

*Torques at intermittent speeds are inversely proportional to speed.



SHADED POLE

MODEL 3000 with GEAR UNIT

TYPE: 2 Pole Shaded Pole.

DIAMETER: 3-7/16".

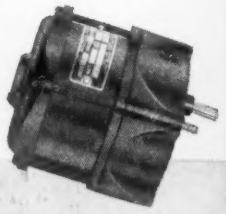
LENGTH: 3-5/8" to 4-1/2".

MAXIMUM CONTINUOUS TORQUE* 1 R.P.M. (at 1-1/2" Stacking Length): 45 in. lbs.

MAXIMUM INTERMITTENT TORQUE* 1 R.P.M. (at 1-1/2" Stacking Length): 70 in. lbs.

BEARINGS: Porous bronze sleeve type with oil reservoir.

*With external fan. Torques at other speeds from 1 to 400 rpm available upon request.



INDUCTION

MODEL 2400

TYPE: 4 Pole Induction.

DIAMETER: 2-9/16" square.

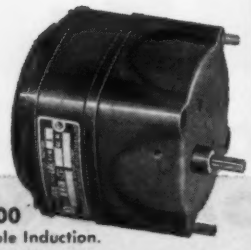
LENGTH: 2-3/8" to 3".

SINGLE PHASE CAPACITOR MOTOR:
Maximum Torque oz. in.—1.
Full Load Speed R.P.M.—1150.
Bearings—RBC—Ball. RWC—Sleeve.

TWO PHASE MOTOR:
Maximum Torque oz. in.—1.5.
R.P.M.—1150.
Bearings: RBT—Ball. RWT—Sleeve.

BEARINGS: Porous bronze sleeve type with oil reservoir, or grease sealed ball bearings.

GEAR UNITS: Ratios 6:1 to 3600:1. Spur gears throughout. The high speed pinion is cut on the shaft, assuring accuracy and concentricity, and maximum strength is achieved by supporting the output shaft in large porous bronze bearings.



INDUCTION

MODEL 2500

TYPE: 2 or 4 Pole Induction.

DIAMETER: 2-9/16" square.

LENGTH: 1-7/8" to 2-3/8".

SPEED: *1200 to 3600 R.P.M.

H.P.: 1/300 to 1/1400.

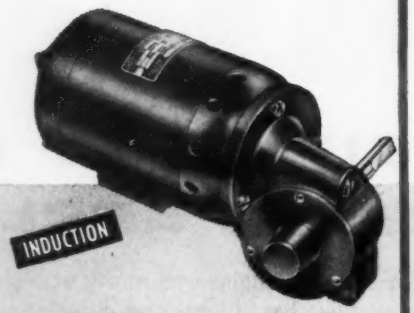
MAXIMUM TORQUE oz. in. *1.6 to 3.5.

BEARINGS: *Ball or sleeve.

*Dependent on type of motor used; i.e. Non-Synchronous Capacitor Motors, Torque Motors, Standard Synchronous Motors, Hysteresis Synchronous Motors.

GEAR HEAD: Ratios from 6:1 to 3600:1. Torques up to 300 in. oz. at low speeds. Range of output speeds from ½ r.p.m. to 600 r.p.m.

Spur gears are used throughout. The high speed pinion, cut on the rotor shaft, assures extreme accuracy, and maximum strength is achieved by supporting the output shaft in large, solid bronze bearings.



INDUCTION

MODEL 2900 with GEAR UNIT

TYPE: 2 Pole, 4 Pole Induction.

DIAMETER: 3-5/16".

LENGTH: 7-5/64" to 8-11/64".

SPEED: 1650 to 3600 R.P.M. depending on type of motor used—Non-Synchronous, Standard Synchronous, Hysteresis Synchronous, or Torque.

H.P.: 1/70 to 1/15 depending on length of stacking.

TORQUE OUTPUT: Up to 60 in. lbs. depending on ratio.

BEARINGS: Permanently lubricated and sealed ball bearings.

RATIOS: 10:1 to 60:1.

UNIVERSAL

MODEL 29-500 with GEAR UNIT

TYPE: Universal AC/DC or Shunt.

DIAMETER: 3-5/16".

LENGTH: 7-13/64" to 7-37/64".

SPEED: 5000 to 10,000 RPM.

H.P.: 1/70 to 1/4 depending on length of stacking.

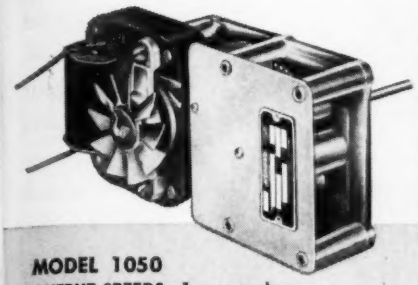
TORQUE OUTPUT: Up to 60 in. lbs. depending on ratio.

BEARINGS: Permanently lubricated and sealed ball bearings.

RATIOS: 10:1 to 60:1.

line of Fractional H.P. Gear Motors

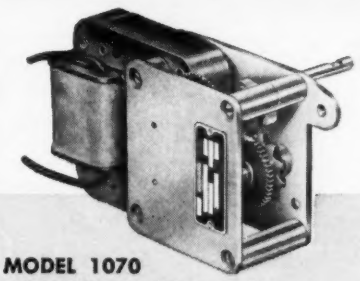
2 POLE, DOUBLE BEARING



MODEL 1050

OUTPUT SPEEDS—1 rpm and up.
GEARS—Molded nylon in high-speed for quiet operation, stamped, cut or sintered in low-speed section.
BEARINGS—Sintered porous bronze with large oil reservoirs for assured self lubrication.
MOUNTING—Front only; choice of ten holes tapped as required.
ROTATION—Unidirectional (CW or CCW).
SHAFT—3/16 in. dia. std. with length to meet requirements.

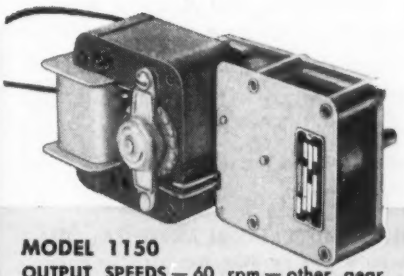
starting torque, in. lbs.	no load rpm	full load					stack A, in.
		torque, in. lbs.	rpm	input (115-V) amps.	input (115-V) watts	gear ratio	
20	6.8	33	6	.34	18	500:1	⅝
15	10.2	24	9	.34	18	333:1	⅝
7	17	19	15	.46	24	200:1	⅝
5	43	11	30	.46	24	100:1	⅝
2.25	75	4.5	68	.46	24	45.4:1	⅝
2.0	122	2.4	108	.75	35	27.8:1	⅝
1.5	159	1.9	140	.81	40	21.4:1	⅝



MODEL 1070

OUTPUT SPEEDS—30 rpm and up.
GEARS—Molded nylon in high-speed section for quiet operation; stamped, cut or sintered in low-speed section. Also available, when specified, with cut gears throughout.
BEARINGS—Sintered porous bronze with large oil reservoirs for assured self-lubrication.
MOUNTING—Front only; choice of three holes tapped #8-32 and/or two .161 in. dia. holes.
ROTATION—Unidirectional (CW or CCW) as specified.
SHAFT—3/16 in. dia. std. with length to meet requirements.

starting torque, in. lbs.	no load rpm	full load					stack A, in.
		torque, in. lbs.	rpm	input (115-V) amps.	input (115-V) watts	gear ratio	
2.25	82	4.5	74	.46	24	37.8	⅝



MODEL 1150

OUTPUT SPEEDS—60 rpm—other gear trains for different output speeds available, state requirements.
GEARS—Molded nylon in high speed section for quiet operation. Stamped, cut or sintered for low-speed section.
BEARINGS—Sintered porous bronze with large oil reservoir for assured self-lubrication.
MOUNTING—Front only, choice of ten holes tapped as required.
ROTATION—Unidirectional (CW or CCW as specified).
SHAFT—1/4 in. dia. std. with length to meet requirements.

starting torque, in. lbs.	no load rpm	full load *					stack A, in.
		torque, in. lbs.	rpm	input (115-V) amps.	input (115-V) watts	gear ratio	
16	75	24.5	60	3.1	124	50:1	1¼

*Intermittent duty (10 seconds On, 50 second OFF continuously).

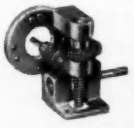
GEAR REDUCTION UNITS

Designed for direct mounting on Howard motors, the speed reducers illustrated in this section give a wide range of speeds and torque in both open and closed types; single or two stage. Closed units are grease packed for efficient lubrication with minimum maintenance. For heavy duty, high torque applications, Models A-7 and A-12 are especially recommended. *Twelve Howard universal motors (not shown) are available as gear motors with the gear units illustrated.*

Hundreds of standard ratios permit accurate selection of output speed. Most of the gear units can be supplied with double shaft extensions where required. Our gear reducers are intended for use only with Howard motors.

Ratings are maximum under ideal operating conditions. Each application requires careful consideration based on having description of Load & Duty Cycle.

MODEL A-1
Single Reduction, Open
Maximum Ratio: 58:1
Minimum Ratio: 3:1
TORQUE
Continuous Duty: 5 in. lbs.
Intermittent Duty: 10 in. lbs.
Efficiency: Max. 45%

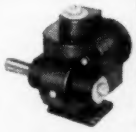


MODEL A-3
Double Reduction, Open, With Mounting Pad
Maximum Ratio: 2700:1
Minimum Ratio: 40:1
TORQUE
Continuous Duty: 5 in. lbs.
Intermittent Duty: 10 in. lbs.
Efficiency: Max. 30%

MODEL A-4
Single Reduction, Closed
Maximum Ratio: 58:1
Minimum Ratio: 3:
TORQUE
Continuous Duty: 5 in. lbs.
Intermittent Duty: 10 in. lbs.
Efficiency: Max. 45%

MODEL A-5
Double Reduction, Closed
Maximum Ratio: 2700:1
Minimum Ratio 40:1
TORQUE
Continuous Duty: 10 in. lbs.
Intermittent Duty: 20 in. lbs.
Efficiency: Max. 30%

MODEL A-6
Single Reduction, Closed
Maximum Ratio: 60:1
Minimum Ratio: 3:1
TORQUE
Continuous Duty: 12 in lbs.
Intermittent: 25 in. lbs.
Efficiency: Max. 65%



MODEL A-7
Double Reduction Closed, Heavy Duty
Maximum Ratio: 2600:1
Minimum Ratio: 21.5:1
TORQUE
Continuous Duty: 50 in. lbs.
Intermittent Duty: 100 in. lbs.
Efficiency: Max. 50%

MODEL A-12
Combined Worm and Spur Gears
Maximum Ratio: 525:1
Minimum Ratio: 6.7:1
TORQUE
Continuous Duty: 100 in. lbs.
Intermittent Duty:: 250 in. lbs.
Efficiency: Max. 50%

MODEL A-26
Single Reduction, Closed
Heavy Duty
Maximum Ratio: 60:1
Minimum Ratio: 3:1
TORQUE
Continuous Duty: 50 in. lbs.
Intermittent Duty: 100 in. lbs.
Efficiency: Max. 80%

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CIRCLE 9 ON INQUIRY CARD

"We insist on the Philbrick amplifier for our new package" says Philbrick

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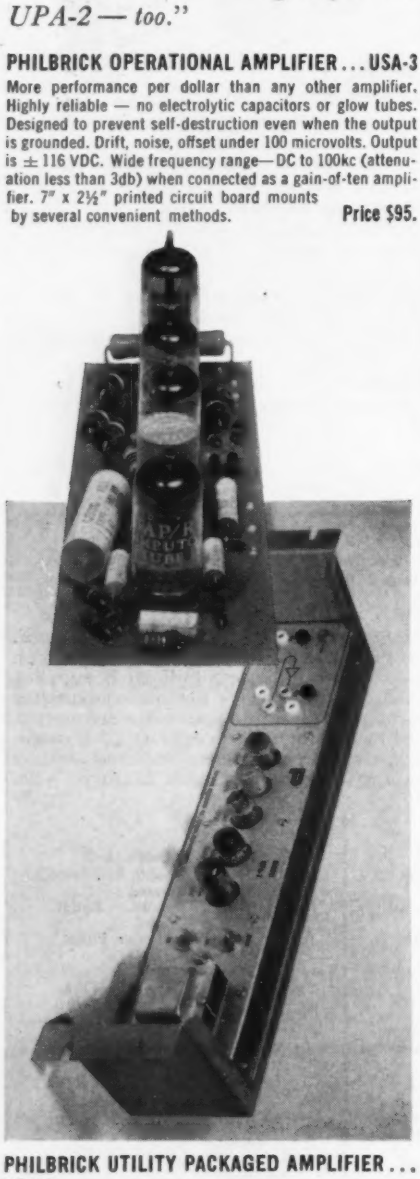
More performance per dollar than any other amplifier. Highly reliable — no electrolytic capacitors or glow tubes. Designed to prevent self-destruction even when the output is grounded. Drift, noise, offset under 100 microvolts. Output is ± 116 VDC. Wide frequency range—DC to 100kc (attenuation less than 3db) when connected as a gain-of-ten amplifier. 7" x 2½" printed circuit board mounts by several convenient methods. **Price $95.**



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Combines new level of flexibility and convenience. Performance characteristics same as the USA-3 amplifier, the heart of this package. Can drive 12,000 ohm load to 100 volts in either direction. Designed for 3½" rack mounting but can be used equally well as a bench amplifier, or plug-in assembly without modification. Use it for analog computing, measurement and control, continuous data reduction, and many other feedback operations. **Price $149.**

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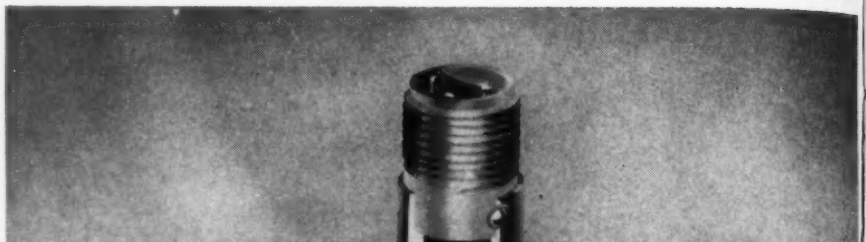


TURBINE FLOWMETER PICKOFF

A-C Carrier Transducer With High Frequency Signal Output

Dynamic flow measurement as well as precision steady-state flow measurements are, at present, almost universally obtained by means of turbine flowmeters. Their principle of operation is fundamentally simple. Fluid flow drives a freely spinning turbine rotor located in a straight-through conduit. Speed of rotation of the turbine rotor is linearly proportional to fluid velocity and, because of a constant area, is linearly proportional to volumetric flow rate. As the turbine rotates, electrical pulses (sine wave cycles) are induced in a coil mounted external to the fluid conduit. Frequency of generated pulses is a measure of flow rate, while total number of pulses is a measure of total volume. Since the output is an a-c signal of varying frequency, the instrument may be classified as a time-digital transducer. This characteristic of turbine flowmeters results in difficulties of resolution not encountered with transducers with analog signal output.

Attacking this and associated problems, the industry has achieved two radical improvements in signal generator design: a "shroud ring" technique increases frequency of signal generation, and an a-c carrier technique improves signal-to-noise ratio at low flow rates. Waugh Engineering Co. of Van Nuys, Cal., has combined these two techniques in a single high-performance transducer. Here are some of the problems in conventional turbine flowmeter pickoff designs and how they were solved in the Waugh Engineering design, as described by Mr. Ralph M. Flygare of that company.

To take advantage of the high frequency response inherent in a lightweight high-efficiency rotor, the velocity of the rotor has to be sampled at frequent intervals. The signal pickoff from conventional turbine flowmeters samples the flow at a maximum rate of approximately 400 times per second. Accordingly, the response time may be of the order of 1 millisecond regardless of the amplitude of the step function. Although the rotor's actual response may be this rapid it may not be possible to actually observe this response since the resolution of the electrical signal pickoff may not permit observing the flow more often than once every 20 milliseconds, for example.

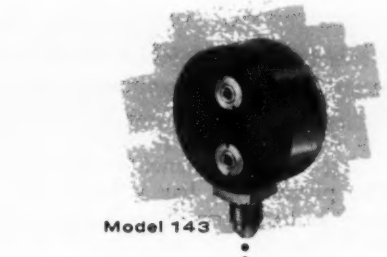
Early designs of turbine flowmeters, Mr. Flygare said, employed a single magnet housed in the rotor hub to generate the output pulses. This arrangement generates one a-c cycle for each revolution of the rotor. Improved designs employed four-bladed rotors in which the magnetic properties of each rotor blade were used to generate a complete a-c signal cycle. Obviously a greater number of cycles per revolution may be obtained by still further increasing the number of rotor blades. A

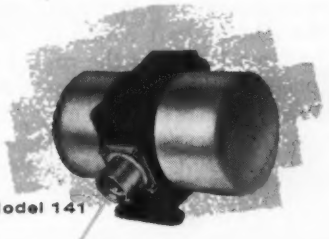
practical limit for the number of rotor blades thus employed is determined by mass-inertia, viscous drag and other effects. This limit varies among the different makes of flow sensors because of many design variables; however, about twelve blades are usually used in flow sensers having line sizes smaller than approximately 2½ inches. To overcome this limitation, a so called "shroud ring" encircling the rotor blades and having a series of slots, holes or other surface discontinuities has been used. By combining the multipole shrould ring with an advanced design high speed rotor, the output signal frequency may be raised by a factor of 5 or more. Transducers having a 2000 cps output at maximum flow are now commercially available.

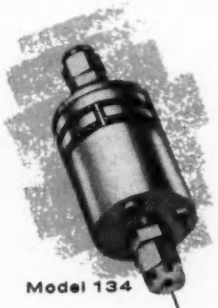
The shroud-ring technique has two additional advantages Mr. Flygare pointed out. Use of a rotor having an optimum number and configuration of rotor blades as determined by hydrodynamic characteristics may be employed without regard to electrical signal generating characteristics. Also, unequal spacing of the shroud-ring holes permits the output signal to be distinctively coded for data reduction indentification purposes.

Aside from the advantages of superior transient response, he added, flow sensors with high output frequency are especially desirable for use with digital flow rate indicators. Digital indication of flow rate is accomplished by electronically counting the number of pulses generated by the flow sensor for a specified interval of time. The count thus obtained is displayed and the process is repeated, usually on an automatic cycling basis. Direct readout in units such as GPM or pounds-per-hour depends on the selection of a time base or sampling interval properly related to the calibration factor (pulses per gallon) of the flow sensor. Since the calibration factor (PPG) of the flow sensor equals the number of pulses per second divided by the flow rate in gallons per second, increasing the output frequency of the flow sensor, increases the number of pulses per gallons. It can be seen that the timing interval can be made smaller by increasing the output frequency. For this reason, high frequency flow sensors are almost always used in practical systems.

The second improvement Mr. Flygare discussed was the a-c carrier type of signal pickoff. Conventional turbine flowmeters use either variable reluctance or magnetic induction methods of signal generation. In the first of these techniques a coil having a permanent magnet core is placed in proximity to the moving part which may be either the rotor blade tip or the shroud-







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MISSILE, AIRCRAFT AND INDUSTRIAL APPLICATIONS

Features:

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  Infinite Resolution
  Wear to 20x10⁶ cycles
- Repeatability: 0.1% full scale
- Temperature: 500°F operation
- Vibration: 20 g's all axes 10 to 2 KC
- Range: 0-1 to 0-7500 PSI

RAHM INSTRUMENTS

DIV. OF AMERICAN MACHINE AND METALS, INC.
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ring. Motion of the rotor varies the reluctance of the external flux path of the coil's magnetic circuit thereby inducing a current in the coil.

The magnetic induction technique employs a coil with a non-magnetized but highly permeable core located in proximity to the moving part which is magnetized. In some instances the rotor is made from a machinable permanent magnet material such as Vicalloy. Other designs use a permanent magnet located within the rotor hub. The moving external field of the rotor magnet induces a current in the coil.

In either technique the amplitude of the generated signal is proportional to the rate of change of the moving part and is not influenced by the magnitude of the displacement. A small excursion of the rotor can, sometimes, generate a sizeable signal when the velocity is high. This characteristic may result in a spurious signal output under conditions of no flow when the transducer is subjected to mechanical vibration from an external source.

Mr. Flygare pointed out that this characteristic results in another disadvantage. At low flow rates the output signal, being a function of rotor velocity, may be an amplitude so small as to have a poor signal-to-noise ratio. Attempts to raise the output voltage level by increasing the number of lines of magnetic flux results in a magnetic drag on the rotor which adversely affects the hydrodynamic characteristics of the transducer. This magnetic drag has an attendant disadvantage in that flux density is usually not uniform from one pickup coil to another. Therefore, pickup coils cannot be interchanged without the possibility of affecting the calibration factor, particularly at very low flow rates. Even at best the output voltage is low, typically a few hundred millivolts, which requires shielding of signal lines and other techniques to minimize electrical noise. To avoid these problems an amplitude-sensitive rather than a velocity-sensitive signal pickoff arrangement is required. The a-c carrier signal generating technique had been used successfully in pressure and strain transducers and suggested itself as a possible means for overcoming the disadvantages discussed.

The carrier method employs a fixed frequency a-c carrier amplitude-modulated directly as a function of the variable to be measured. The Waugh flowmeter with a carrier type pickoff employs a nonmagnetized, but highly permeable, shroud-ring similar to those previously described for use in conventional turbine flowmeters. However, the magnetic circuit differs in that an a-c magnetic field is provided by an external coil. Changes in the external magnetic flux path resulting from motion of the rotor alter the inductance in one arm of a bridge circuit thereby balancing and unbalancing the bridge. The pickup coil has a laminated "E core" and comprises the bridge inductance element. In actual practice, two coils are employed in separate arms of the bridge circuit with both coils being physically located at the flow pickup; only one of these is influenced by the motion of the rotor. This arrangement minimizes balancing adjustments of the bridge to account for line length, temperature effect, etc. The coil excitation frequency is several times higher than the modulation frequency obtained at full flow. Practical design considerations dictate that the carirer frequency should be approximately ten times the maximum modulation frequency. The bridge output is demodulated to provide an a-c signal whose frequency is proportional to the flow rate. The wave shape of the demodulated carrier envelope reflects changes in inductance at the pickup coil. A square wave will result from a sharp break in the flux carrying circuit while a sinusoidal wave will be obtained by the flux pattern occurring when a rotor blade tip moves through the excitation field.

It can be shown that the optimum carrier frequently is determined by the core's permeability, the width of the laminations and the coil's a-c impedance. A practical design employs a laminated core of high mu 80 metal and a coil inductance of approximately 2.85 mh at 3500 cps.

The bridge output is demodulated by a full-wave rectifier the output of which is supplied to a high-Q low-pass filter. Ideally the filter output should be down 12 db or more per octave above the maximum modulation frequency.

The actual ratio between the carrier frequency and the modulation frequency is further determined by the amplitude of the null-point signal.

Waugh flowmeters with these improved signal generators are now in use in advanced design military aircraft. Transistorized and miniaturized circuitry has been used for supplying the carrier frequency and demodulating the output. Airborne oscillographs for recording transient flow phenomena have been very successfully used in those instances in which telemetry has not been employed. Also, engine test stands have been advantageously instrumented with these flowmeters since transient flow measurements in the presence of severe noise and vibration are frequently encountered in these applications.

Circle No. 88 on Inquiry Card

Low Noise Silicon Transistors

Two new NPN silicon transistors feature noise levels comparable to the best available vacuum tubes. Specified at typically high noise frequencies (from audio down to one cycle per second), the ST1050 has equivalent input noise voltage of about one microvolt RMS when used with low source impedances. Applications include thermocouples, strain gauges, accelerometers and other devices in the 100-500 microamp range.

A second transistor, the ST1051, offers low noise current of 0.05 millimicroamps RMS and is designed for use with high source impedances. ST1051 is suited for 20-50 microamp operation, typical current range for ionization gauges, geiger tubes and photocells. Transitron Electronic Corp., Wakefield, Mass.

Circle No. 165 on Inquiry Card

Subminiature Delay Lines

Precision lumped constant delay lines in a new subminiature case are suitable for transistor and printed circuit applications. These delay lines consist of subminiature powdered-iron toroidal inductors and temperature-compensating ceramic-disc capacitors in a lumped constant configuration phase and frequency compensated for optimum pulse response. They are packaged in a 1 x 4-inch metal tube with glass-to-metal end seals to bring out pigtail-type leads. Seven units are included in this series with characteristics ranging from 0.1 microseconds delay, 0.03 us rise and 500 ohm impedance to 0.7 microseconds delay, 0.23 us rise and 1,600 ohm impedance. Available in kit form. Valor Instruments, Inc., Gardena, Cal.

Circle No. 226 on Inquiry Card

Miniature Strain Gage Transducer

Small strain gage transducer, intended for the measurement of gage, differential or absolute pressures, is accurate within an operating temperature range of −65F to +250F and a pressure range of 0-10 to 0-200 psig. Only 0.25 inches in diameter by 0.31 inches in length, this flush diaphragm unit has natural frequency of about 7,000 to 20,000 cps with infinite resolution. With an output of 15 millivolts full-scale open circuit and a nominal bridge resistance of 200 ohms, the dependable accuracy of the output signal and the small size of the unit make it suitable for direct use or, to obtain up to 5 volts DC output, for use with a strain gage carrier amplifier. Statham Instruments, Inc., Los Angeles, Cal.

Circle No. 222 on Inquiry Card

Circle No. 13 on Inquiry Card→

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HACKENSACK, NEW JERSEY

ZERO-LENGTH UNBONDED STRAIN GAGE

New Strain Gage Configuration Simplifies Transducer Design

Unbonded strain gage instruments have advantages for many applications:

- **Infinite resolution.** In practice, resolution is limited only by the electrical characteristics of the receiving instrument.
- **Long operating life,** because there is no friction of mechanical parts during operation. For the same reason, reliability is very high.
- **High natural frequencies,** due to smaller size and lighter weight of moving parts as compared with most frequently used types of transducers.

Conventional unbonded strain-gage transducers, however, present certain problems to the transducer designer that make his work a high art. The Zero-Length strain gage designed by Statham Instrument, Inc., Los Angeles, Cal., applies a new principle to strain-gage transducer design that sidesteps the major problems. Fig. 1, describing a conventional four-element unbonded strain gage illustrates design problems the conventional configuration presents.

- Point A must be restrained by positive stops from moving so far as to break the wire.
- The wire must have an initial tension carefully controlled during assembly to give it exactly the correct operating tension when it has been heated by the necessary electric current from the bridge power supply.
- Initial tension is subject to instability due to dimensional changes in the instrument parts which separate points A and B, caused by thermal expansion or contraction. This problem cannot be avoided by making the instrument parts of material of low thermal expansion, because the parts must obviously be made of material matching the thermal properties of the strain wire itself so that everything will contract or expand together. Moreover, this idea of matching materials would not be completely satisfactory because the thermal masses of the wire and of the instrument parts are so vastly different that they do not change temperature at the same rate. Hence problems arise during thermal transients.

The fact that the distance AB possesses a finite value is therefore the source of much trouble. If this distance between the moving and the fixed points (gage length) were nominally zero, the problems enumerated above would disappear.

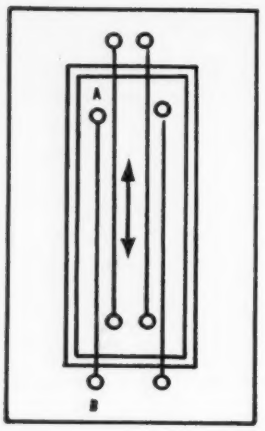

FIG. 1. Conventional unbonded strain gage transducer. The transducer is electrically and mechanically symmetrical. In the center of a stationary frame, an armature is supported rigidly in the plane perpendicular to the longitudinal axis. Wound between rigid insulators mounted in the frame and armature are four filaments of strain sensitive resistance wire. The filaments are of equal length, arranged as shown. As the armature is caused to move longitudinally by an external force, one pair of filaments increase in length while the other pair decrease in length. Change in resistance of the filaments is proportional to their change in length. Resistance change of the filaments alters the electrical balance of a Wheatstone bridge to produce an electric signal in the output circuit.

In the new Zero-Length unbonded strain gage the wire is not stretched between a moving and a fixed point of longitudinal separation. Instead, the moving and fixed points are longitudinally superimposed. Fig. 2(a) is a schematic diagram showing the principle.

Point A is the moving point whose position is to be measured. Point B is fixed. Point C is free, but is rigidly attached to a weight M whose function is to keep the wire taut. When point A moves, the load M is transferred smoothly from one half of the strain wire to the other, and the gage elements AC and BC are thus caused to change strain equally and oppositely, producing equal and opposite changes in resistance. Electrical connections are made at A, B, and C, so that the gage elements AC and BC operate in push-pull.

The sum of the forces in the two gage elements is a constant and is always equal to the force exerted by M. If the weight of M is slightly less than one strand of the strain wire can carry, the wire is safe from breakage by over-traveling of A.

Within the operating range of the gage, point C always moves exactly half as far as point A, until all of the weight of M has been transferred from one wire to the other. The value of M merely controls how far point A will move before a complete transfer has taken place. The sensitivity of the gage in terms of electrical output per unit of displacement of A is independent of M.

In practice, for the sake of simplicity, it is advantageous to substitute for M a weak but long spring as shown in Fig. 2(b). If the spring rate is low, it serves effectively as a substitute for M.

Fig. 2(c) shows how the principle of the Zero-Length unbonded strain gage is used to construct a complete

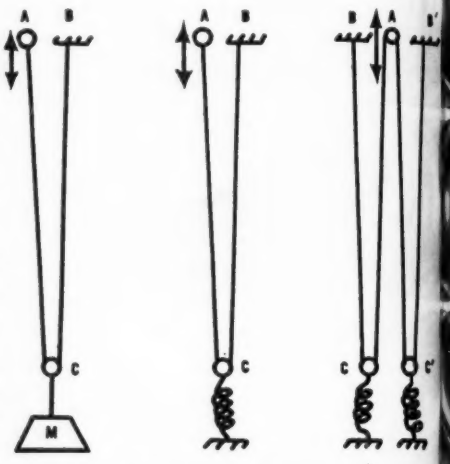

FIG. 2. Schematic diagram showing principle of Statham's Zero-Length unbonded strain gage.

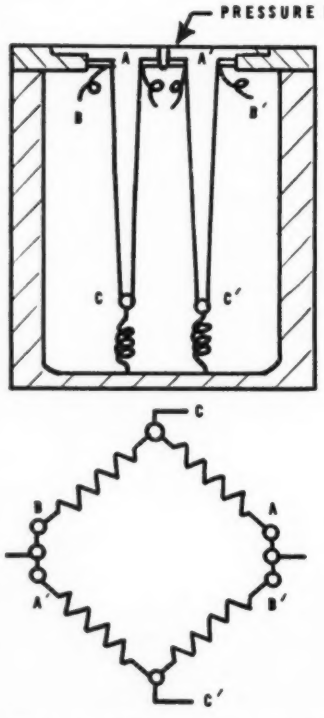

FIG. 3. Configuration of Zero-Length strain gage in a pressure transducer.

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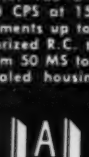

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bridge with all four elements activ

A pressure transducer incorporatin the gage is shown in Fig. 3.

Since over-travel of the moving point cannot overload the strain wire, the wire may be worked very close to its elastic limit with safety. Thus, the Zero-Length gage is capable of substantially higher output than conventional gages. In practice, twenty-five millivolts output per volt input is easily achieved. The gage can also operate at higher input voltage than the conventional gage, because the increased temperature does not cause the wires to go slack. The spring takes up the slack.

Employing the Zero-Length unbonded strain gage principle, Statham Laboratories, Inc., have developed a series of transducers for measurement of strain, pressure, and acceleration.

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Direct Current 28 Volt Motor

Operating on 28 volts DC, new motor delivers 2.0 horsepower at 3,000 rpm. This motor is of the open frame construction and features integral cooling fan. Standardized flame quench rings are available to provide complete explosion proof feature, as is a radio noise filter to meet MIL-I-6181B. By removing the reduction gear box, you can get higher output speeds. This motor features a patented brush holder whereby even brush pressure is obtained over the full wear range of the brush, thus producing an even power output motor and permitting high altitude operation with minimum brush arcing. Hoover Electric Co., Columbus, Ohio

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Ultra Precision Potentiometer

25 turn, 2 inch diameter, ultra-precision pot has linearity as close as 0.0075% and very high resolution. Overall length is 2-9/16 inches including bushing mount—only slightly longer than most ten turn units. Ceramic core provides a dimensionally stable, chemically inert and non-hygroscopic foundation. Modified slope control delivers accurate servo-controlled winding. Litton Indus., Inc., Mt. Vernon, N.Y.

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Extended Temp Range TR Tubes

New line of extended temperature range TR tubes is self-contained and capable of meeting all standard electrical and mechanical specification between temperatures of −55C and +125C. Interchangeable with present JAN TR tubes, the new tubes are available in all bands. Bomac Laboratories, Inc., Beverly, Mass.

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WORTH FILING

Silicon Rectifier Handbook

Here's a just off the press two color, 48-page silicon rectifier handbook covering silicon rectifier theory, operation, manufacture, performance characteristics, electrical ratings, dimensional drawings and design application data. A must for design engineers involved with silicon rectifier applications.

Source: Sarkes Tarzian, Inc.
Bloomington, Ind.

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Ceramic Transducers

Glennite high temperature, piezoelectric ceramic transducers have exceptionally high Curie points enabling higher output voltages per unit input pressure than with conventional ceramics. Since no cooling is required, applications in ordnance systems and high temperature electromechanical sensors are possible. Brochure on transducers describes components and their applications in fields of underwater sound, ultrasonics, medicine, shock and vibration, and in general equipment.

Source: Advanced Development & Systems Div.
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Synchronous Motors and Controls

"Synchronous Motors and Controls", 27-page illustrated booklet, contains motor selector charts, application data and formulas for calculating power factor. A quick summary of types and features of motors and controls includes a discussion of power factor correction, considerations in selecting motors and special application problems.

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Bronze Welding Electrodes and Filler Rod

Reference data charts give information on comparative bronze electrodes, melting rates and efficiencies, electrode and filler rod specifications, and recommended welding currents. An electrode technical data chart describes Ampco's weldrod color code, deposit density, number of electrodes per pound and feet per pound of bare rod. Data are also included on all arc welding processes, with necessary equipment, type and size of electrode or rod, and polarity for each process.

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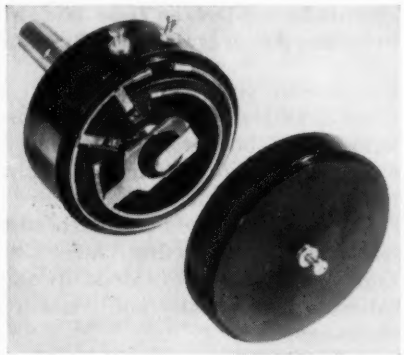

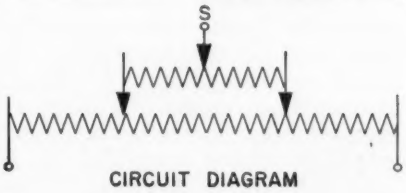

CIRCUIT DIAGRAM

VERNIER POT

10-Turn Resolution in 2-Turn Size

Applying the vernier principle to potentiometer design, Rinco, Inc. of Portland, Oregon has developed a 1-¼ inch diameter unit with 0.02% resolution. Their Type 301-A Pot includes a vernier resistance concentric with a portion of the main slide wire. The vernier slider attaches directly to the shaft and contacts the slider terminal through a suitable slip ring. Attached to the vernier frame are two contacts which slide upon the main slide wire approximately 15 degrees apart. This segment of the main slide wire is effectively spread over 270 degrees of vernier rotation. When the shaft is rotated to the limit of the vernier slider, a mechanical stop is engaged transferring the shaft rotation to the vernier frame and causing the spaced contacts to slide upon the main slidewire to provide course adjustment. Reversing shaft rotation then adjusts the vernier to desired fine setting.

The less than two revolution control of the adjustment range allows substantial adjustment time savings, of special significance in multiple potentiometer installations such as in electronic computers and data logging systems. The Type 301-A RINCO-POT is a precision device capable of long life performance in high accuracy applications.

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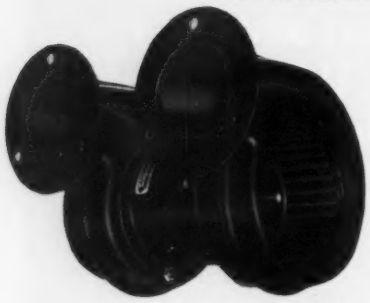

YS BLOWERS

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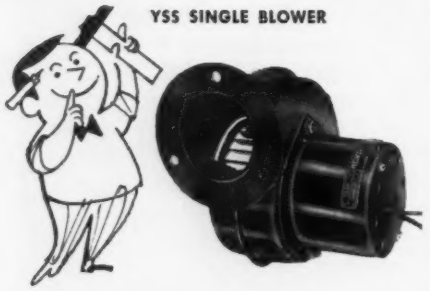

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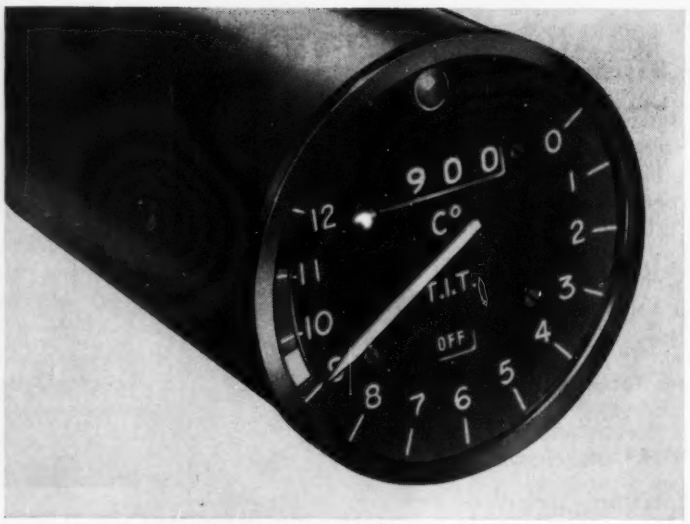

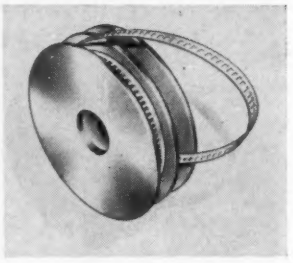

Tape-slidewire arrangement that carries the slidewire embedded in its edge is perforated along its other edge and mounted on two spools as is motion picture film. By varying the distance between centers of adjacent holes a few thousandths of an inch, a non-linear resistance to hole count relation can be established. The tape is transported between the two spools by means of a servo-driven sprocket wheel with tapered teeth. The tape, with its resistance wire and non-linear hole spacing, is in effect a very accurate and basic analog-to-digital converter. A digital indicator geared to the sprocket wheel drive shaft provides final indication.

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For several years, military test engineers have been using a potentiometer with a tape-slidewire in jet engine test equipment where extreme accuracy is required. Consistent performance of this unique slidewire has influenced the manufacturer, B & H Instrument Co. of Fort Worth, Texas, to extend its application to new military and commercial instruments.

A most recent application is an analog-to-digital indicating millivolt meter with laboratory accuracy. Contained in a case 3″ x 5″ x 5⅜″ deep, and weighing less than 3 lbs., the instrument has a guaranteed accuracy of 0.1% and infinite resolution. It is a completely self-contained, servo-driven potentiometric unit with transistorized amplifier and Zener referenced power supply.

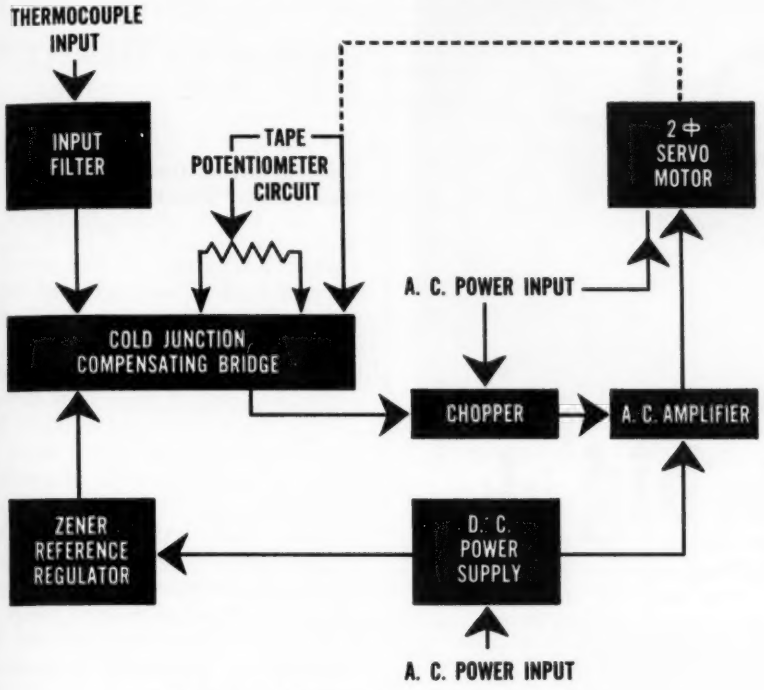
The slidewire that makes this instrument possible is formed by bonding a resistance wire within one edge of a laminated Mylar tape. The tape, 144 inches long in the standard unit, is calibrated in an automated test system where it is compared to a master tape, 60 feet long. During calibration, the tape is perforated for engagement of a positioning and driving sprocket. Digital values can also be printed on the tape for direct readout. In response to coded signals placed upon the prepared master tape, the hole spacing or printing is varied to conform to the ratio desired between the digital indication and slidewire resistance. Up to 100 calibration points per foot of slide-wire length can be made.

This procedure conservatively guarantees, for either linear or non-linear functions, calibration to 0.1%, linearity (conformity) to 0.05% and infinite resolution.

Used with a transducer employing a strain gage as the measuring element, the instrument forms a system for indication of weight, pressure, force, etc., with a direct digital reading in any units desired. In such a system, the 0.1% accuracy of digital indication matches the capabilities or accuracy of the strain gage transducer.

Used with a transducer whose output is resistive in nature (such as resistance thermometers or thermistors), the system provides a direct reading, digital indication of narrow temperature span in an operational unit that exceeds the capabilities of much laboratory equipment.

The instrument is available with two readout arrangements:



Schematic diagram of AutoTemp unit.

1) With the calibration printed on the tape and viewed through a window in the front of the case, linear parobolic, hyperbolic or logarithmic functions in any scale units can be presented with an accuracy of 0.1%.

2) With a digital-in-line counter geared to the slidewire drive shaft, functions with a variation of 15% in slope can be accommodated.

Slidewires with resistance from 100 ohms to 100K ohms are available. In this instrument the slidewire is contained on two spools by a sprocket drive which engages holes punched in the Mylar tape. Standard full scale travel is 6 to 10 seconds.

When calibrated as a pyrometer for use with any thermocouple, this linearized digital indicator has automatic cold junction compensation. Guaranteed accuracy as a pyrometer is 0.1%.

As an a-c bridge, the instrument can be calibrated to correct for droop or any non-linearity. With differential transformers, it can be calibrated to produce a linearized digital indication with great accuracy for pressure and flow applications.

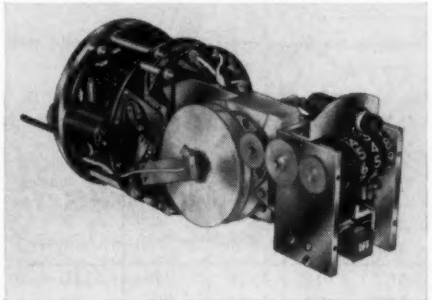
Available for use on 115-volt 60- or 400-cycle power, the instrument requires 20 VA.

Since this millivolt meter is basically a very accurate analog-to-digital converter for linear and non-linear inputs, provision has been made for the inclusion of binary and decimal contact-making counters to provide a signal source for punched tape, magnetic tape, computers and for programming and controlling. Switch contacts are rated at 100 milliamps, 115 volts.

Provision has also been made for the addition of a re-transmitting slidewire as a signal source for recorders, telemetering and analog computers.

With a pulsed or sine wave input, the unit has been used as a tachometer or frequency meter with a range of 0 - 800 cycles, and is accurate to 0.1%.

Calibrated for use with turbine type flow meters that produce a pulsed output, the instrument will display instantaneous rates in digital form . . . . in either volumetric or weight units.



Internal assembly of AutoTemp unit.

These instruments are currently available in two series, the BH180 AutoTemp series and BH170 AutoTak series. They are varied as to tape or counter readout, with or without contacts, hermetically sealed or not sealed.

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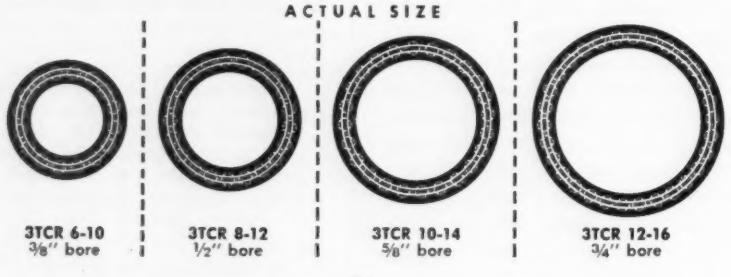

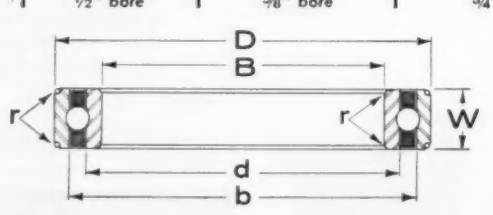

*B bore ± .0002	*D o.d. + .0000 − .0004	W width + .0000 − .0050	†r radius	b outer land ± .001	d inner land ± .001	Balls no.	Balls size	‡L lbs.	§S lbs.
.3750	.6250	.15625	.010	.542	.457	16	1/16	77	110
.5000	.7500	.15625	.010	.672	.587	21	1/16	89	144
.6250	.8750	.15625	.010	.797	.712	24	1/16	94	165
.7500	1.0000	.15625	.010	.922	.8375	30	1/16	101	206

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Taking advantage of the newly developed highly compact and efficient silicon diodes, Servo-Tek Products Co. of Hawthorne, New Jersey, has combined them with a markedly improved d-c tachometer of their own design to provide the basis for a fractional horsepower speed control system using a d-c motor, operable from the 60 cycle line. This timely combination possesses the efficiency and flexibility of d-c motor control, precision of closed loop operation, usual compactness, simplicity and reliability. Standard models range from 1/40 to ¾ horsepower, and are available with an assortment of features including reversibility and speed indication or readout.

Fig. 1 shows the closed loop system in schematic form and describes its mode of operation. The special characteristics of the Servo-Tek system are essentially those of any closed loop control, as listed in Table I. Typical performance specifications are listed in Table II.

The fractional percent accuracies indicated in Table II are based, in the main, on the accuracy of the feedback tachometer. Principle problems in this type d-c tachometer have been the result of erratic and nonlinear character of the brushes. Brush drop has been particularly variable when units were operated at very low currents. The drop has little or no relation to the specific resistance of brush material, but is directly related, rather, to the resistance properties of the microscopic film of material that develops between brush and commutator surfaces after a period of operation.

Drop in voltage due to commutator film is easily reduced by addition of highly conductive materials such as copper, silver, etc. to the graphite brush material. This, however, creates new problems: erratic variation in film resistance, apparently due to the nonhomogeneous nature of the brush material; a shorting resistance which develops between commutator segments due to increased conductivity of brush dust. The shorting resistance, after a period of use, causes an erratic output.

Servo-Tek has achieved near-perfect stability by careful selection of brush

and commutator materials, brush tension, and commutator design. The availability of this improved d-c tachometer as a reliable control system component may lead to considerable expansion of its application.

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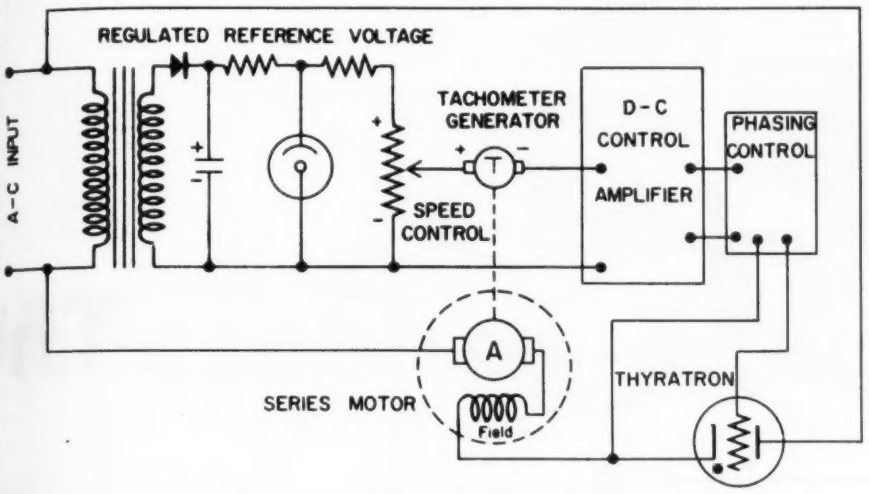

FIG. 1—A portion of the regulated reference voltage is tapped down as required to set speed. This voltage is compared with the tachometer output. Differences are amplified and applied to the phasing control, which in turn modifies the voltage applied to the series motor, correcting its speed.

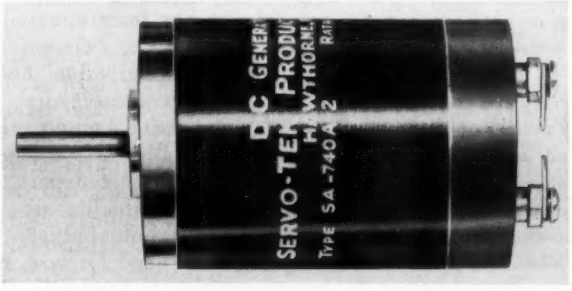

FIG. 2—Precision tachometer, heart of the feedback speed control system.

TABLE I

PRECISION SPEED CONTROL CHARACTERISTICS

Advantages

1—Line voltage changes have no appreciable effect on motor speed.
2—Very wide useful speed range.
3—Speed virtually independent of motor temperature.
4—Continuous-duty rating at any speed.
5—Speed held substantially constant regardless of changes in motor torque load.
6—Speed changes due to component aging are minimized.
7—Capable of precise adjustment of speed at any convenient location.
8—Speed has a highly linear, relationship with the controlling reference voltage; it is well suited for precision control or integrator applications.

Disadvantages

1—Higher initial cost.
2—Approximate 1-minute warm-up is recommended after power is first turned on.

TABLE II

PERFORMANCE CHARACTERISTICS, SERVO-TEK SERIES 100 PRECISION SPEED DRIVES

SPEED RANGE: Infinitely adjustable from zero to rated speed. The useful speed range is in excess of 100:1. Constant torque is available at any speed throughout a 100:1 speed range.

LOAD REGULATION: As high as a 50% change in load will result in a speed change of less than 1/2 of 1% of rated speed.

LINE VOLTAGE versus SPEED: At a given load, the speed change resulting from a ± 10-volt change in the supply voltage will be less than 1/4 of 1% of the rated speed.

SPEED versus DIAL SETTING: Actual speed at any constant load and at any dial setting will deviate from a truly linear relationship by an amount that is less than 1/2 of 1% of the maximum rated speed.

DUTY RATING: Can be operated continuously at full-rated torque at any speed.

STABILITY: After a five-minute warm-up, the speed variation over a 48-hour period will be less than 1/2 of 1% of maximum rated speed.

OVERLOAD PROTECTION: Readily accessible dual-element fuses provide maximum protection while permitting temporary overloads.

DYNAMIC BRAKING AND REVERSING: A reversing controller is available to provide both braking and reversing. All functions are relay-operated, using low-voltage control circuits that can be located at any convenient distance. The use of relays facilitates the automatic control of special purpose machines or automated equipment.

SPEED INDICATION: Control heads are available with a 4½" meter to indicate speed. On all models a scale is calibrated to read "0-100 PERCENT OF FULL SPEED."

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The hi

This article "Philosopher-Executive", was taken from "The Tao of Science," copyrighted by the Massachusetts Institute of Technology and published jointly by the Technology Press and John Wiley and Sons, Inc.

In the preceding 14 chapters, Dr. Siu touches upon the ancient roots of modern science. He uncovers the shaky uncertainties on which our facts and methodologies are grounded. He observes the pitfalls in the use of logic, especially when shrouded in the ambiguities of language. He alludes to the inability of science to clarify the deeper significance of life. He hints at a deepening wedge that the abstractive domination of modern science is driving between herself and humanity. And, at the same time he searches encouraging avenues for a renaissance of science in devotion to the welfare of man. He discusses the negative method of education, imparting a deep awareness of nature without jeopardizing the development of specialists. He covers the Median Way of leadership. He points out the re-assessed contributions of organized research. He pinpoints the expanded freedom of growth in social effort. And he covers the concept of no-knowledge.

Throughout his text he covers the philosophical and aesthetic bases of research management in a diffused manner. In chapter 15, he asks the question: *Just what characteristics should executives in research ideally possess in order to gain the objective delineated in the previous chapters?* Here he attempts to describe this personality.

An impression exists among some circles that a staff of renowned scientists has no particular need for exceptional leadership. The reputation of such an organization will sustain its chief. All that the presidency requires is a successful money procurer with a charming personality. In consonance with this attitude, too frequently a mediocre scholar has been shunted into the directorship of research institutions, because the "good men" have been retained at the individual investigative level. This way of thinking degenerates leaders into minor administrators of routine intellectual consequence. They provide no inspiration of great pith nor command any significant respect.

Actually, the more expert the men in the organized effort, the more valuable are their skills, the more significant are their potential contributions, and the more exacting is their need for wise management. A deep concern must be given to the most effective employment of these precious talents. The more spirited the stallions, the more skilfully must the reins be handled. It is even said in the ancient Chinese *Book of History*: "In ruling over the people, I feel as if I were holding six horses with worn-out reins."

The direction of human beings is a matter of artistry, rather than procedures and formulae. For a simple analogy, we can draw on the study of Pareto on the effect of demand upon supply. With a community of a hundred persons, exchanging seven hundred products, he

RECEPTIVE TYPE THE EXPLOITER TIGHT-LIPPED HOARDER THE MARKETER

Born in Honolulu, R.G.H. Siu was educated at the University of Hawaii and at California Institute of Technology (Ph.D.). He has been a Research Fellow at the Pineapple Research Institute and the California Institute of Technology, and a Research Associate at Harvard University. Since 1945, he has been affiliated with the U. S. Army Quartermaster Corps where at present he is Technical Director.

R. G. H. Siu

The Philosopher—Executive

showed that 70,699 simultaneous equations were necessary to determine the prices which would balance out the demand and supply. With a population running into millions, the requisite equations would reach a completely unmanageable number. This led him to conclude that the market, not the mathematician, was the best guide to the management of prices.

In exercising research leadership the director is faced with far greater hurdles. He is dealing with subtle yet passionate commodities, human will, imagination, and mental constructions in a world of emotional capacities to implement distant events felt acutely. To make conditions conducive to a canalized direction requires an intimacy with the poetic and artistic features of life, as well as a skill in manipulating human labor and pecuniary power. There must be a penetration beneath the stilted managerial outlines of programs, budget, personnel, reporting, and systems of communication. Such topics form the pedagogic chants for the training of junior executives. By themselves, however, the administrative factors are like figures in Madame Tussaud's wax museum. They give a general idea of what the living form should resemble but nary a twitch of life. Pope's famous couplet is a useful summation:

For forms of government let fools contest;
Whate'er is best administer'd is best.

A lively direction of research dovetails diverse characters into a collective course of action. Let us see who some of these actors are.

There is the receptive type. He is highly dependent on others for help, constant support, and inspiration. He feels lost when left alone and is extremely sensitive to rebuffs. He is helpless at making definite decisions. He scans the walls unendingly and cowers under the shelter of advisers and committees. He is paralyzed by doubt.

There is the exploiting type. Like the receptive individual, he, too, feels that the source of good is outside himself. However, the exploiter grabs, steals, and presses partisan advantage to the bitter end. Loyalty, humility, and respect are foreign to his make-up. He plagiarizes, indulges in senseless bickering over authorships, and bedecks himself with the honors that rightly belong to his associates. He compliments those he continues to exploit and disparges those squeezed dry.

There is the tight-lipped hoarding type. He squats behind the protective "no." Things outside his fortress are suspect; they have not been invented therein.

There is the marketing type. He is constantly concerned with what the traffic can bear. Exchange value rather than use value is his focus of attention. The program must be fashioned for highest remuneration from the current fashion train. How can he get on? How can the

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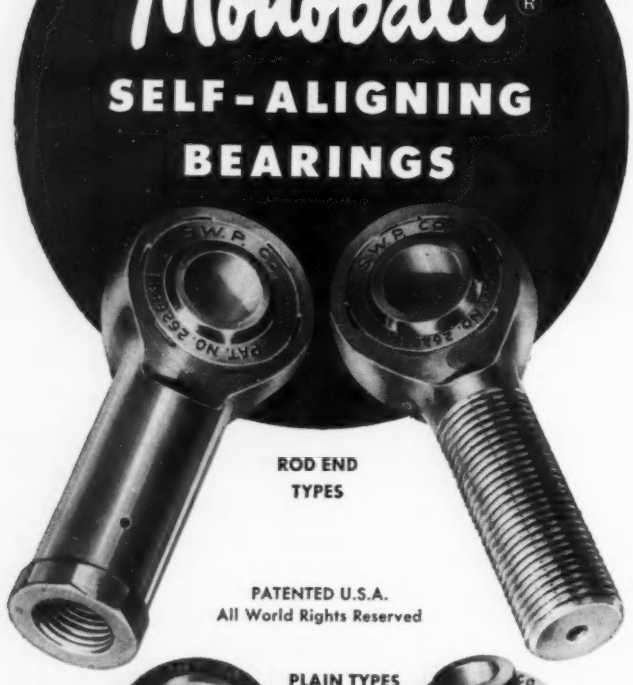

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research be sold? What constitutes the most attractive wrapping? are his chief worries. The substance of the effort is purely ancillary.

There is the envenomed type who is continually jaded by his own ineptitude and sterility. He seeks to raise his relative position and reputation by constantly sneering at and looking for the worst weaknesses in his co-workers.

There is the frustrated type. He had once tasted the uplifting satisfaction of creativity but now is beginning to realize a drying up of his powers, being forever denied the ambrosial rewards reserved for the greats. Although he is still very capable and can contribute very significantly using the talents he does have, his mind is preoccupied with the recognition that he is just not quite good enough to be the great man he wants to be. He soon loses faith in himself and frequently winds up a leading fanatic in one cause or another.

There is the sincere creator. He is imbued with the ardor for new messages of increasing goodness for his fellow men, without particular concern for credit and honors. His potentialities and powers are fully developed to the limit of his natural ability to the advantage of society.

The list of behavioral types just presented partly follows Freud's and Fromm's discussions. We may incorporate other classifications, such as the delightful Taoist breakdown of smugs, snugs, and humpback (to borrow Lin Yu-tang's translation):

> **Smugs are those people who having heard what their teacher says, feel very satisfied and very pleased with themselves. They think that they have learned the truth and do not realize that there was a time when no material universe existed.**
>
> **The snugs are lice on the bodies of hogs. They choose their abode in the long mane and hair of the hogs and believe themselves to be living in a grand palace with a big garden. They hide themselves in the corners, armpits, breasts and legs of the pigs and think that they are living in security. They do not realize that one day the butcher may come and rolling up his sleeves to lay hay under it and set fire to singe the pig and both themselves and the pig will be scorched to death. This is to live within the limitations of their own choice.**
>
> **The humpback was Emperor Shun. The mutton does not crave for the ants but the ants crave for mutton because of its rank smell. Emperor Shun had a rank character which attracted people; the people loved him. Therefore, after he changed his capital three times and had moved to the plains of Teng, there were over a hundred thousand people who followed him. Emperor Yao heard of Shun's ability and put him in charge of a barren district, saying, "I hope that people who follow him there will receive the benefit of his rule." When Shun was put in charge of the barren district, he was already old, his eyesight and hearing were failing, but he was not allowed to retire.**

Whether or not our coverage of personalities is complete is immaterial for our purpose. It suffices to point out that a laboratory is made up of quite diverse characters. To emulsify them into a smooth blend is not a job for the high-handed boss who sweeps everything before him. It is not a task for the old-line efficiency expert of charts and figures whose iridescence of life has long since been extinguished in the inkwell. It is not a chore for the flaccid Pollyanna who believes that forfeit of leadership through intellectual anarchy is the fountainhead of fruitful scientific management. It is not a charge for the inflexible scientist whose insistence on free creativity is distorted into a withdrawal from cooperation with other men. It is

a task for the philosopher-executive.

The philosopher-executive extends his horizons beyond hard dollars, cold science, and inert plans. He must focus his determined purpose against the constantly shifting screen of politics, business, intellectual prejudices, scientific fashions, personality conflicts. In particular he is capable of handling the ever-recurring decisions involving conflicts in codes and desires. The laws of the land, the ethical tradition of his superiors, associates, and subordinates, the code of management, the aims of the parent organization, the humanitarian equity of the moment, the professional practices of the many disciplines represented are forever contending for dominant influence.

There is accordingly a continuing conflict of values confronting the executive in his judgments. A multiplicity of objectives vies for a scarcity of means. When the choice involves the mutual exclusion of conflicting codes, the greatest test of his sagacity arises. He has no guiding principle for the resolution of specific cases involving the juggling of differential abilities, priorities of demands, and probabilities of returns. As a consequence of these multifarious pressures toward varying ends, each involving multiple alternate means, full satisfaction rarely is meted out to any one side.

In cases of conflict, does the executive bludgeon through one plan? Such are the tactics of the tough tycoon. Or does he recall the old Chinese adage: When choosing between alternatives of grave import but involving high uncertainties, one should choose that path which if proven wrong results in the least harm? This is the safest solution. Or does he create a new action which dissolves the original conflict? This is the rare executive talent which requires an excursion into the regions of the not-not of the Buddhist truths in the higher sense discussed in Chapter 4. The same problems confront the manager of the most abstruse of research programs as well as the most practical of corporations.

Competition for limited rewards happens in the very best of families. The Cistercian monk Thomas Merton described episodes of contention among Jesus Christ's personally picked team: "More than once Jesus had to rebuke His Apostles who were wrangling among themselves and fighting for the first places in His Kingdom. Two of them, James and John, intrigued for the seats on His right and left hand in the Kingdom."

To discharge his various obligations in style, the philosopher-executive covers the integrated whole of experience with a triple insight—the dreaming, the understanding the acting.

To begin with, the philosopher-executive is able to join his researchers in their dreams. It is mostly in dreams that one finds the delightful overtones that make life decorative, the ideals that spur man's efforts, the genial sensitivity to the nobler aspects of life, the soothing charm and heroic wit that cheer men's lives, the grace notes that beautify the theme of the laboratory, the glimpses of the ever-receding and reappearing patterns that fuse into the unity of the universe. Without dreams one is bound to the ordinary conventions of the waking hours. There is no inspiration. After all, are not scientific concepts but dreams petrified? Inability to dream strangles the source of the raw stuff of science.

In sharing the dreams of others, the philosopher-executive reveals a natural responsiveness through passive receptivity. He is the appreciative listener. As Walt Whitman has said: "To have great poets there must be great audiences too." He suspends knowledge and evaluation in his attention to the dreams of his scientists. A sympathetic ear has no diaphragm of discrimination. The very act of judgment implies a comparison and condemnation.

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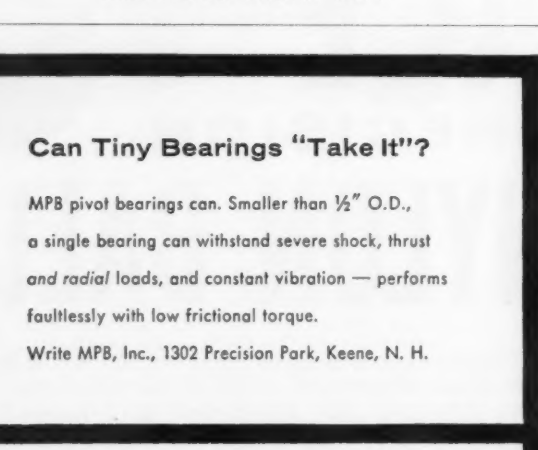

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When we condemn immediately, we think we understand the dream but we do not, and a separation has been introduced between the judge and the judged. In place of judgment there must be an awareness, with no reference to particular standards, codes, or choices. The dream must be sensed as it is dreamt. If we let our experience and intellectual attitudes be deva sentries through which a proposal must pass before it receives an audience with our mind, we will never get a new idea. Every suggestion that conflicts with our past will be judged, condemned, and refused admission. The windowless wall of experience imprisons the rock-ribbed conservative, who mistakenly feels secure behind his own cult of the Ego. An executive should develop the state of self-forgetfulness and purge away every taint of self-consciousness. This will enable him to let go of himself and latch on to the dreams of others. He should not emulate that self-oriented character of Hawthorne's story, *The Intelligence Office*, who is continually crying out, "I want my place, my own place, my proper sphere, my thing to do, which nature intended me to perform when she fashioned me thus awry and which I had vainly sought all my life."

Dreams fall upon the mind of the philosopher-executive like a scene upon a clear mirror. Only after they have been given the freedom of their full impact is his entire experience, including the dream, conjured forth in a novel totality. In this way the dream does not become merely an accretion to experience like a barnacle to a ship. It is assimilated in a recasting of the entirety into a fresh harmony.

To share the dreams of creative artists requires a sympathetic appreciation of their strong leanings and idiosyncracies. Some are self-centered and conceited; some are naive and intolerant of the practical; but all have a talent for creativity. The wellsprings of their dreams lie in their passions, instincts, and desires. These cannot be suppressed, for the source will soon be clogged by frustration and only nightmares sputter forth through the cracks and fissures. In short, the philosopher-executive loves people, not books, figures, rules, and charts. His feelings are identified with his neighbor's. He shares the sentiments of Su Tung-po, who, returning home one New Year's Eve after presiding over a court trial of prisoners arrested for salt smuggling, composed the following poem:

On New Year's Eve, I should go home early,
But am by official duties detained.
With tears in my eyes I hold my brush,
And feel sorry for those in chains.
The poor are trying to make a living,
But fall into the clutches of the law.
I, too, cling to an official job,
And carry on against my wish for rest.
What difference is there between myself
And those more ignorant than I?
Who can set them free for the time being?
Silently I bow my head in shame.

In his no-knowledge, the philosopher-executive does not seek perfection among his associates. He recognizes the slimy trap of harping on deficiencies. He understands the simple truth that mortals are full of defects. Criticizing the obvious lends neither prestige to the critic nor aid to the recipient. He remembers the Confucian comment to the effect that when you see a good man emulate him, but when you see a bad man examine your own heart. This does not mean that the philosopher-executive goes about in a sackcloth or cloaked with a self-centered sense of holy duty toward others. He just goes about naturally, subconsciously extending understanding and sympathy without conscious effort. The selflessness of his self-forgetfulness is contrasted to the overt selflessness of others of exaggerated convictions.

Yet the philosopher-executive does not dream on forever. He comprehends what lays down the rules of the game, what provides measure and taste, what limits are circumscribed for the scientific method, how they are influenced, what brings forth the endless series of opposing forces and compromises, and how close the total complex in reality can move toward the fantasy of the dreams. Dreams may wander beyond the bounds of rationality to bring back inspiring possibilities. But before they take form in the company's till, they must first put on the garb of realism. In the words of Emerson: "Of what use is genius if the organ is too convex or too concave and cannot find a focal distance within the horizon of actual life?"

It is the researcher's anxiety regarding the supervisor's appreciation of dreams that protests, perhaps in silence, against control by executives with inferior competence in the specialties. Latent in such an attitude is the implied sense of superiority in intellect and judgment by persons of those particular trainings. This narrow view is a misconception of the function of leadership. It is true that technical awareness of the subject matter is of great import as an ingredient of understanding. For this reason, the philosopher-executive has usually passed through the intensive period of a specialized discipline and attainment. He has an intimate feeling of the aspirations of the research mind. However, the astuteness of conducting esoteric research is not sufficient, nor for that matter necessary. It may be essential in the detailed guidance of others in the field. But overextended specialization may sever one's emotional link with society at large, leaving him progressively unable to sense the thoughts and motives of men in general. The responsibility of the leaders of research is to weld people of different talents and tempers into an integrated activity. Obviously the philosopher-executive cannot be a peer to the investigators themselves in the respective branches of science. He is, however, their superior in perspective, judgment, synthesis over a wider front of human interests, and understanding of Eliot's shadow, which falls:

Between the idea and the reality
Between the motion and the act. . . .
Between the conception and the creation
Between the emotion and the response. . . .

To be practical is a matter of degree and relevance. Life on this planet, after all, is said to be good for only another two billion years. According to the best guess, at that time the sun will burst and the earth will turn into gas. If this long-range eventuality serves as the sole determinant to action, there is little reason for beautifying and improving man's world only to meet the incineration and gasification of all man's efforts. But reasonable living has an immediacy factor. There must be a recognition of the margin of error, the degree of elasticity and the point of reference that govern each action. To be practical in terms of Shylock is to hoard; to be practical in terms of Senator Claghorn is to be elected; to be practical in terms of Attila the Hun is to plunder; to be practical in terms of St. Francis of Assisi is to love. If the point of reference is extended to ultimate questions, we have the philosophers of the classical tradition. If it is focused on forging a link between the immediate activity and an order of remoteness beyond that of common farsighted business, we have the philosopher-executive.

In the implementation of dreams, the philosopher-executive is infused with a love for learning. He recognizes the six "becloudings" of Confucius:

You have heard the six becloudings? There is the love of being benevolent without the love of learning, the beclouding here leads to foolish simplicity. The love of knowing without the love of learning, whereof the

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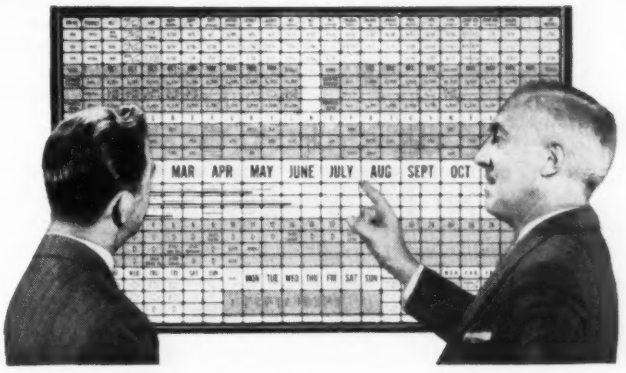

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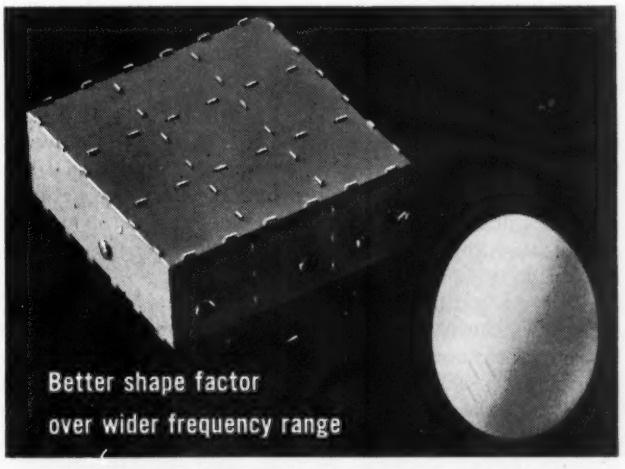

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beclouding brings dissipation of mind. Of being sincere without the love of learning, here the beclouding causes disregarding of consequences. Of straightforwardness without the love of learning, whereof the beclouding leads to rudeness. Of boldness without the love of learning, whereof the beclouding brings insubordination. The love of firmness without the love of learning, whereof the beclouding results in extravagant conduct.

The efficient management of organized research also demands gusto and quickened action. "He who would train in the fortress of contemplation," as the saying of Gregory the Great goes, "must first train in the camp of action." It is only in participation that the final synthesis of knowledge can be embodied in a unitary attitude to life. A faulty execution of a sound plan generates no more beneficial an outcome than a sound execution of a faulty plan. Some executives have even gone so far as to say that nothing is right which does not work. This may be too extreme a pronouncement. Yet, of what service to humanity is a dream entombed? Unless results are effected, the dreamer will continue to share the bewilderment of the March Hare, who was trying to fix the Mad Hatter's watch with butter in *Alice in Wonderland*. All he could say was: "And it was the *best* butter too, the *best* butter."

The art of getting things done involves the processes of making decisions and of doing. The goals of the parent concern must always be kept clear. Decisions must be made in their reflected light. The philosopher-executive knows what to do, when to do it, to whom to assign the task, and when to stop. Actions must be directional. The objective cannot be attained by flailing at generalities in a pointless dissipation of energy. The philosopher-executive heeds the ancient Persian proverb: "He who learns and learns and yet does not (take action on) what he knows is one who plows and plows yet never sows." Accordingly, if his parent organization is an industrial concern, his actions result in better products, increased consumer satisfaction, profits for investors, and improvement of the life of employees. If it is a government agricultural establishment, they lead to improved crops and animals, better farm practices, and benefit to the farmers, ranchers, and consumers. If it is a university, they stimulate scholarship in learning, integrity in beliefs, no-knowledge in feeling, and a humane vector in action.

The philosopher-executive also faces up to the problems of human frailties. He prunes the deadwood from the organization in such a fashion as to preserve equally the integrity of management and the respect for employees. He recognizes the captious power plays and wily pettifogging by that occasional unscrupulous minority. Wisely, he does not reciprocate in sly tactics and tricky circuities. He has learnt well the lesson about not wrestling with pigs: "You get dirty and they enjoy it!" For it has been said: "In shallow water dragons become the laughing stock of shrimps." Nevertheless, the philosopher-executive knows the ramifications of the circumstances and the effective means of dissipation of their damage.

In exercising sovereign prerogatives, the leader inevitably incurs the obstinacy and animosity of some associates. The same happens to the philosopher-executive, however altruistic he may want to be. He recalls that even the saints were not regarded as saints by all men. Otherwise, they would not have been stoned, crucified, and burnt. Confucius' advice to Tse-kung is well taken on this score. He was asked, "What would you say if all the people of the village like a person?" "That is not enough," answered Confucius, "it is better when the good people of the village like him and the bad people of the village dislike him."

The philosopher-executive recognizes that great works emanate from dedicated sincerity. If the creator is actuated by the will to goodness, he will untiringly pursue the hidden vagueness of unfinished experiments until he penetrates to the very heart of the problem. He will ferret answers from the far reaches of his mind. Ideas dredged from the very bowels of his soul are bound to bear the stamp of originality, for no two investigators are prototypes to such depths. He will also be impelled to communicate the fullness of his findings in the clearest expression so that others may be infected with the same enthusiasm and share in their use. When the lust for discovery is enkindled by quick adulation and quick gold, there will be trolling only in shallow waters. The fishing lines of these researchers cross each other. Concepts emerge entangled and similar; readers are barraged with hollow claims of priorities and enlarged snapshots of minnows of invention. The more insincere the researcher, the more puerile the emerging science.

Executives, too, need to be sincere. By sincerity the Taoist means a naturalness in no-knowledge. We cannot explicitly define such a state of naturalness. But we may look at what the Taoist call the "pure men of old." Chuang-tze has spoken about them at length. A few representative snatches may provide a suggestive picture.

The pure men of old acted without calculation, not seeking to secure results. They laid no plans. Therefore, failing they had no cause for regret, succeeding no cause for congratulations . . . So far had their wisdom advanced toward Tao . . . [they] slept without dreams, walked without anxiety. They ate without discrimination drawing deep breaths. For pure men draw breaths from their farthest depths; the vulgar from their throats . . . [they] do not injure others but do not credit themselves with charity and mercy . . . They act differently from the vulgar but take no credit for their exceptionality . . . They appear to smile as if pleased, when actually it is but a natural response from the store of goodness within themselves . . . They appear to desire silence when in fact they had dispensed with language.

In his deep understanding of the interrelatedness of events and the nature of the minute seed that is destined for its matured expression, the philosopher-executive frequently implements the ultimate by injecting the early imperceptible germinal influence. He then lets nature with her many men of action develop the inevitable. One often wonders, for example, what would have been the present international picture had the Pope agreed to send the hundred learned scholars versed in the "seven arts" requested by Kublai Khan through Marco Polo in 1266.

Practically everything that has been written in this chapter so far can be derived from a common-sense approach. This is all to the good, for common sense is part and parcel of the suchness of nature that the Taoist stresses so much.

In addition, everything the philosopher-executive does "feels right." This "feel-rightness" is a common experience: the golfer who "senses" the perfect drive at the instant of contact of the club and the ball, the actor who "sees" that the audience is with him after his first lines, the lecturer who "is sure" his points are getting across, the negotiator who "knows" he is on the verge of a workable agreement. This "feel-rightness" has the quality of enduring. When things "feel right" there is a sense of enduring communication, of intimacy, of mutuality. A perfect communion with the suchness of nature provides the latent enduring which is not forced. All things fall into their proper places, so to speak. The philosopher-executive understands that all things do not fall into their proper places if some are left out, if some are distorted, if some are forced.

In many respects, the philosopher-executive is much attracted to Henri Bergson, as when he said in his letter to William James, "I saw to my great astonishment that scientific time does not endure . . . that positive science consists

in the elimination of duration. This was the point of departure for a series of reflections which brought me by gradual steps to reject almost all of what I had hitherto accepted and to change my point of view completely." But then, Bergson's separation of scientific time from animate time and his stressing of pure dynamism and emphasizing that becoming is more of reality than that which becomes lead to a slight parting of the ways. The philosopher-executive, much as he appreciates becomingness, does not wish to be preoccupied with any one separate facet of nature at a time.

In many respects, the philosopher-executive is much attracted to Alfred North Whitehead, as when he wrote, "In a certain sense, everything is everywhere at all times. For every location involves an aspect of itself in every other location." But then, Whitehead's fundamental rule ". . . that events have parts and that—except in a derivative sense, from their relation to events—objects have no parts" leads to a slight parting of the ways. The philosopher-executive does not wish to think in terms of "parts."

In many respects, the philosopher-executive is much attracted to George Santayana who attempted to develop a philosophical system out of many different alliances by "combining them as well as logic allowed without at heart ever disowning anything." Indeed, he is deeply sympathetic to Santayana when the poet-philosopher is accused of a lack of clarity. But then, Santayana's splitting up of his world philosophy into four realms leads to a slight parting of the ways. The philosopher-executive wonders how the four realms are fused. And why were there just four, anyhow? he asks himself as he muses over the infinite shades of nature.

In many respects, the philosopher-executive is much attracted to the worldly-wise philosopher, who recognizes the limitations of man and the practical realities of society and is satisfied with small increments of gain for the alleviation of human pain and the reduction of ignorance. But then, the well-intentioned vigorous pursuit of piecemeal attainments along a single or a few selected facets at a time leads to a slight parting of the ways. The philosopher-executive rather expects that restrictions to such approaches can but result in a disharmony in the whole.

Thus it is that the philosopher-executive shares much of the attitudes of many philosophical schools—but not completely. This indescribable residue after all the differences have been accounted for is the inspiration that the philosopher-executive derives from the ineffable continuum of nature, something pervasive, something enduring, the final presence of which enables him to "feel right" at each instant of action or inaction. And after the episode is past, everybody on the side lines will be able to sit back and say, with a certain degree of truth, "Why, that is just what *I* would have done. It is the *natural* thing to do."

In essence, the action of the philosopher-executive is guided by the proper pace of no-knowledge. Inwardly he cultivates spiritual enduring; outwardly he performs in social beneficence. He develops, in the phraseology of the old Chinese, "sageness within and kingliness without." The maintenance of this stature in his personage as a leader in society is his highest exemplification of responsibility.

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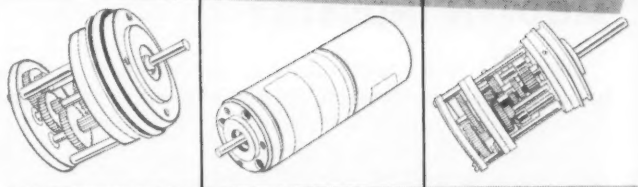

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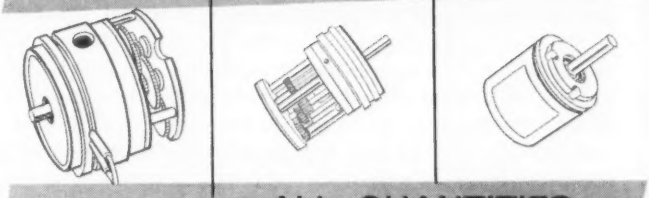

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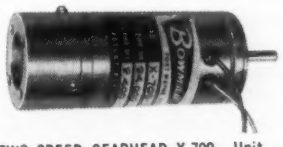
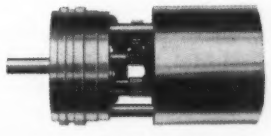
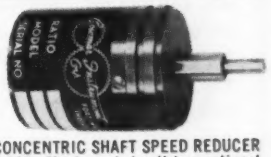


TWO SPEED GEARHEAD X-709. Unit shown has speed reductions of 2400:1 and 24000:1 for fast approach and slow zeroing. Unit is electrically actuated and is completely self contained. Typical of many Bowmar designs currently being manufactured.



PRECISION SERVO MOTOR GEARHEAD 750-GH (with housing). Standard ratios to 2000:1; Starting torque: .005 in.-oz.; Load torque: 5 in.-oz.; Backlash: 30 min. max.; Diameter: .750 in. Typical of many Bowmar designs currently being manufactured.

PRECISION MINIATURE SPEED REDUCER 1062. Standard ratios to 4000:1. Starting torque: .005 in.-oz.; Load torque: 25 in.-oz.; Backlash: 45 min. max.; Diameter: 1.062 in. Typical of many Bowmar designs currently being manufactured.



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MANAGEMENT

STAFF COLUMNIST
Hyman Olken
Head, Standard Specification and Information Group
UNIVERSITY OF CALIFORNIA—RADIATION LAB.

That inventive capabilities of engineers can be improved by appropriate training is now an accepted idea. At least 18 technical schools give courses to increase inventive ability. Such training generally is euphemistically called "creative engineering". Currently, creative engineering literature stresses a psychological climate favorable to creativity. However, Mr. Olken believes, it is high time to go beyond this and provide the mental exercises by which inventive ability, like any other mental proficiency, is developed.

INVENTING AND ITS PLACE IN MODERN INDUSTRY

Inventing is a vast and vital technological activity about which there is widespread misconception and very little critical thinking.

In the minds of most people the word "inventing" calls up a miasma of wishful thinking of the "wish-I-were-one" type. This mental fog stems from the concept of an inventor implanted by grade-school books. That concept pictures the typical inventor of about 1850 as he was known to the people of his time. In this concept the inventor is seen as a rather "queer" individual with a "gift" for inventing who leads a life devoted solely to attic-tinkering in quest of his invention. And he pursues this life until at long last he achieves some industry-revolutionizing invention like the vulcanization of rubber, the grain reaper, the telephone, or the incandescent lamp. Then he enjoys the rich reward of a great triumph over a skeptical and disbelieving world. Furthermore, Hollywood's glamorizations of the lives of inventors have cast such high-intensity limitation on this concept that the mental haze generated in most people's minds by the word "inventing" takes on luminescence.

In the world of trained scientific and technical personnel there is equally widespread and abysmal misconception about inventing. But in these circles the misconception is of a different nature and arises from a different source—from the belief, among scientists and engineers, in the creative omnipotence of "organized" research. For, almost to a man, the professional scientists believe that if you put enough trained scientific workers together in great research laboratories, and if they all work by following the "analytical approach," no technological problem will remain unsolved."

This leads to the conception, widespread among scientists, that "organized" research has made inventing an outmoded method of achieving technological developments. Hence inventors are considered relegated to the minor technological role of "gadgeteering"; that is, to the production of those minor technological developments required for the marginal fringe of modern industry, such as automobile accessories, household gadgets, and other "gimmicks."

A truer picture about inventing in the present day is more like this: Inventors and inventing are still very much with us. Industry has changed tremendously since 1850 with the great advances that have taken place in science and technology but the inventor's calling has not become obsolete or disappeared; it has become drastically altered to keep pace with this change.

But since then, especially since Edison's invention of the incandescent lamp, industry has grown vastly more technical and far more complex. To establish new industries now requires such highly technical devices as the television camera tube and the cyclotron; and these devices are woven into the fabric of such vast industrial complexes as television broadcasting systems and atomic energy plants.

To keep pace with the vastly more technical and complex nature of industry, the inventing art has had to change radically. Inventing today is still the creative mental process it always has been. But to produce industry-founding or industry-revolutionizing inventions now requires people who not only have good inventive talent but who, in addition, are equipped with good technical education and are trained to invent by a methodical inventing procedure. Today, as in the past, a good many people are born with talent for inventing. Three main groups of inventors now exist.

By far the largest group are those who have inventive talent but have not acquired a technical education and are not trained to follow a methodical inventing procedure. They generally spend their lives inventing myriad variations of household gadgets, and similar devices.

Another large group are those endowed with talent for inventing and who have acquired a good technical education, but have not been trained in a methodical procedure of inventing. These inventors spend a lifetime laboriously evolving and teaching themselves such an inventing procedure, and they invent the mountains of "detail" or "improvement" type of technical inventions that pyramid in heaps, one upon another, to bring our existing industries, machines, and processes to their present high state of refinement.

Finally, among those endowed with inventive talent and who have acquired a technical education there is a small group who also have the aptitude to evolve spontaneously for themselves, and train themselves, in a methodical inventing procedure. These inventors each produce a host of inventions of the type that create new industries or revolutionize old ones.

It is my belief that the function of inventing is accomplished by the same mental process, regardless of how simple or complex the thing invented may be; and that from an understanding of this process a rational, methodical, inventing procedure can be developed. I also believe that, if trained in this procedure, the members of all the groups of inventors mentioned above will produce more inventions, will produce inventions better suited to industry, and will produce them faster and more efficiently.

In this series of columns, I propose to set forth a basic understanding of the mental process of inventing, and on the basis of this understanding to develop a methodical inventing procedure.

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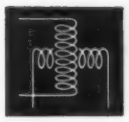

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Available with integral compensating windings. Can be provided with trimming networks to match existing isolation amplifiers or Kearfott-designed transistorized amplifiers.

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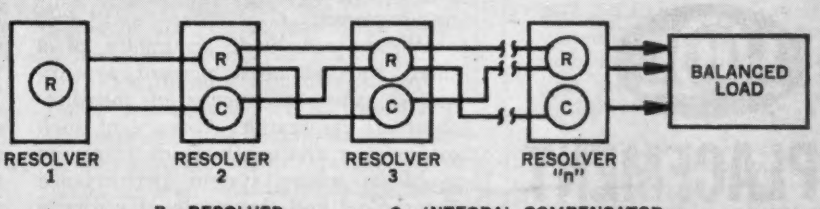

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Primary Impedance	629 + j2510	450 + j2200	220 + j1000	3000 + j (0 ± 40)	1630 /78.5°
Secondary Impedance	695 + j2750	500 + j2300	240 + j1100	3000 + j (0 ± 40)	1620 /80°
Transformation Ratio (Primary to Secondary)	.980	.980	.980	.775	.980
Transformation Ratio (Compensator to Rotor)	.985	.985	.950	.775	.985
Phase Shift (Lead)	8.5°	7.5°	8.5°	0° ± 10'	1°
Fundamental Null (MV)	15	15	8	15	15
Bridge Error From E.Z. (Max.)	7 mins.	5 mins.	3 mins.	3 mins.	20 Seconds
Primary	Stator	Stator	Stator	Stator	Stator

Non-Compensated Resolvers

Basically for application in precise data transmission systems. These synchro resolvers permit system designer to achieve system errors of better than 1 minute of arc without using 2-speed servos and elaborate electronics. By proper impedance matches up to 64 resolver control transformers can also operate from one resolver transmitter.

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Excitation Volts (Max.)	26	11.8	11.8	115	90	90
Frequency (cps)	400	400	400	400	400	400
Primary Impedance	170/77°	850/80°	2000/80°	400/80°	800/80°	8500/80°
Secondary Impedance	42/80.5°	1000/79°	8000/76°	260/80°	900/80°	14000/80°
Transformation Ratio	.454	1.000	1.906	.7826	1.000	1.278
Max. Error from E.Z.	3 mins.	3 mins.	3 mins.	20 seconds	20 seconds	20 seconds
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CIRCLE 32 ON INQUIRY CARD

STANDARDIZING AND MEASURING PRECISION TRANSDUCERS

The most precise transducers develop an output voltage proportional to the product of line voltage excitation and the measured input displacement. This property allows the transducer to be used with line operated servomechanism or closed loop control components in balancing circuits of very high accuracy. Small fluctuations in line voltage and frequency do not materially affect balance, and consequently, highly regulated power supplies are not required.

Where transducer accuracies of a small fraction of a percent are required, adequate means of measurement are imperative. Absence of such means very frequently leads to severe problems where system performance is marginal and the origin of errors is uncertain. Because of the accuracies involved, and the difficulties of debugging precision test gear, "throwing together" such gear with any assurance of its adequacy is almost impossible. It is essential to anticipate the need in advance.

The basic ingredients of a test set are illustrated in Fig. 1. The transducer and the reference standard are both line operated. The reference standard is set so that its output voltage is the same percentage of line voltage as is the transducer output for a particular mechanical setting. If the transducer output is shifted in phase by a specified amount, then so also must be the output of the reference standard. The error detecting circuit measures the difference between ideal (reference standard) output, and the output of the transducer. Because it measures only the error, the error detecting circuit need not be very precise. Often an ordinary millivoltmeter is satisfactory for this purpose. Where vector components of error are required, more elaborate detectors must be used.

A complete transducer check is carried out by setting the transducer mechanical input to a series of values, and comparing with corresponding settings of the reference standard. These checks may be repeated at different temperatures, or other special environmental conditions, to provide a complete picture of transducer performance. The test circuit of Fig. 1 is especially convenient for measuring such characteristics as zero drift, noise (for example, during vibration) waveform distortion, and similar factors which may be relatively inconspicuous until separated out from the fundamental output in the null circuit. Zero drift with temperature, a most important characteristic, is readily observed on the error detecting circuit.

Directly associated with the process of error measurement is *standardization*. To appreciate the significance of standardization, remember that in normal production even very precise transducers vary in their impedance characteristics by factors as high as 5 or 10%. This in no way detracts from the accuracy of the input displacement versus output voltage characteristic, except insofar as scale factor (insensitivity) and perhaps zero setting are concerned. With precision potentiometers for example, there may be substantial variation in total resistance, end resistance, and angle of travel, without affecting independent linearity rating.

Standardization, as we use the term here, may consist of those trimming operations that define a zero and scale factor, as commonly carried out in precision potentiometer circuits, and other transducers. Trimming potentiometers, fixed resistors and capacitors, and other network elements are arranged in networks to permit precise setting of important characteristics prior to measurement of linearity or conformity in a circuit such as shown in Fig. 1. Precision potentiometers, once standardized, are *commonly directly* coupled to a reference standard potentiometer for continuous measurement of error throughout the angular range. Use of a brush recorder to detect errors provides a permanent record of accuracy.

The standardization problem has additional facets. When networks are applied to the output circuitry, sensitivity diminishes and output impedance increases. Output capacitance makes the transducer scale factor (and phase shift) more sensitive to frequency shifts. Input circuit elements have significantly more power handling capacity and are consequently larger. The standardizing elements have to handle significant power and at the same time maintain a high degree of stability, costly characteristics to achieve in the same component. All in all, input standardization is prefer-

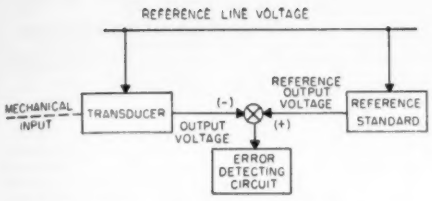


FIG. 1. Basic test circuit components.

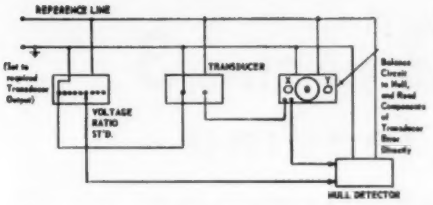


FIG. 2 Transducer balancing circuit.

able, but each application must be judged on its own merits.

Very frequently, temperature (or frequency) compensation is combined with the standardization circuit to maintain accuracy over a range of those parameters. A thermistor network, used in place of a fixed resistor in the primary of a magnetic transducer can maintain accurate scale factor over a range of temperatures adequate for most military specifications.

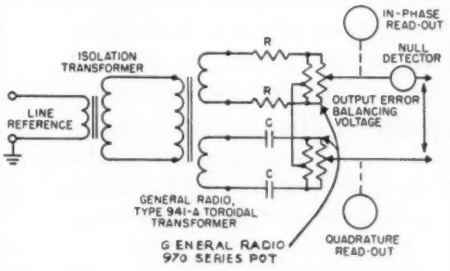
Standardizing circuit elements may be incorporated in the transducer, they may be located externally, or both. Often *fixed* components of the standardizing circuit may be packaged in a neat external network. If these networks are to be interchangeable, the components must be specified to very high accuracy, usually to a small fraction of a percent. Tolerances greater than this probably would require corresponding serial numbers for transducer and external network and interchangeability would not be possible. Selected or adjustable resistors, and of course, temperature compensating elements, are most satisfactorily packaged with the transducer where possible. In any case, external networks are a nuisance to use, since space must be provided, additional parts stocked, and circuitry is more complex. Alternative arrangements must be individually evaluated.

The points discussed above apply equally to the subject of null voltage cancellation. Networks are readily devised to cancel out the fundamental component of null voltage. If such networks are incorporated in the final application, they are installed prior to the accuracy test by the circuit of Fig. 1. Packaging considerations are the same as for standardization and compensation.

Sometimes the trimming and compensation circuits, and other system adjustments aside from those of the transducer, may be combined to give an optimum overall system adjustment. A common adjustment point, for example, is at the summing resistors, which establish relative scale factors. Overall adjustment permits cancellation of some errors, reduces the number of components, and simplifies circuitry. On the other hand, replacing an individual component may require "realigning" the system, a task which usually calls for skilled technicians and a good deal of equipment.

TEST EQUIPMENT DESIGN

Although most precision transducer application is in the relatively low frequency 400 cps and 60 cps range, the designer would do well to think in terms of RF, or at least high audio. Where test equipment accuracy is of the order of hundredths of a percent (to check tenths of-a-percent transducers) the problems of shielding, ground loops, proper location and orientation of components, etc., are fully as important as on more conventional circuitry at much higher frequency. The relatively high output impedance of many transducers makes indiscriminate shielding with consequent introduction of stray capacitance a particularly troublesome problem. Inasmuch as stray output capacitance can never be entirely eliminated, many tansducers are standardized with a fixed defined load, which



Isolation transformer eliminates dissymmetrical capacitance in toroidal bridge input transformer. Tight coupling and symmetry of toroidal transformer minimizes pick-up and inductive fields. Output error balancing voltage connected to sum of transducer and balancing reference voltage.

FIG. 3 Error-balancing circuit. Because the output voltage is only a few percent of the line voltage, the series dropping capacitors, C_1, are sufficient to provide an essentially 90° phase shift of quadrature voltage. The bridge-type circuit permits continuous nulling with no switching required at the phase reversal points. The output potentiometer resistances are kept low, to minimize pick-up.

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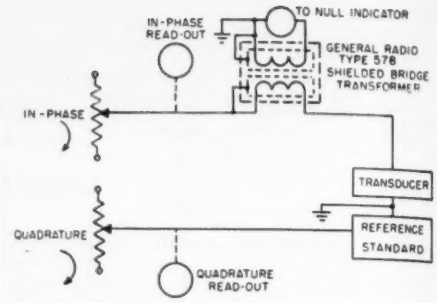

FIG. 4(a) Output portion or error balancing circuit.

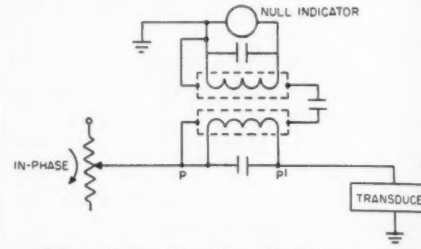

FIG. 4(b) Detail of bridge transformer grounding circuit. Stray capacitance to individual shields is represented by the capacitors across the primary and secondary windings. Capacitance between shields appears as an equivalent capacitor from point P to ground, a light load on the output potentiometers of the error balancing circuit. Capacitance from the high side of the transducer to point P^1 is a direct load on the transducer, and must be minimized by careful wiring.

includes a parallel capacitance element. The stray capacitance in the application circuitry can then be trimmed to match the standard load value. Of course, when output impedance varies with transducer mechanical input, the output function will be more or less affected, a factor which the manufacturer must anticipate and correct for in his design.

Since transducer primary circuits frequently draw appreciable power, the lead wires, which themselves may have to be twisted and shielded, should be of adequate capacity to introduce negligible voltage drop. When extremely high accuracies are required, significant errors may result from too small lead wires.

Grounding of frames, transducer magnetic circuit and case, test chasses, etc., must be carried on in accordance with absolutely best practice. Grounding problems may require days or even weeks of debugging if proper advance consideration has been omitted.

SHIELDING AND SELECTION OF COMPONENTS

Naturally a great deal of grief can be avoided by selecting high grade components for the test equipment. This is particularly true where the engineer is relatively inexperienced in test equipment design and fabrication. He will

not be able to anticipate the problems an unsuitable component may lead to, nor will he be able to explain why one of two apparently similar transformers

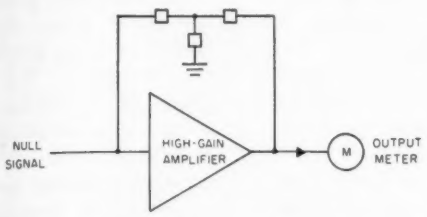

FIG. 5 A sharply-tuned twin-T notch network in the feedback loop of the high-gain amplifier permits full gain for the notch (signal) frequency, while the gain falls toward unity at frequencies far from the notch frequency. A rejection ratio of 100:1 is easily achieved by this means.

operates much more satisfactorily than another. Of course, the experienced man knows where he can save money on non-critical hardware, and he can view the design problem in a somewhat different light. We will illustrate this point specifically with reference to some circuits described below.

TEST CIRCUITS

This section considers the specific components that go into a typical measuring set for the evaluation of precision transducers. Fig. 2 shows the separate components in block form. The arrangement is essentially as indicated in Fig. 1 with the exception that the null detector is used merely to indicate a null while a separate balancing circuit with relatively small full scale output measures error. The figure shows a vector-balance which nulls "X" and "Y" error components. Thus, the reference signal is set to match the ideal transducer output, the separate balancing circuit, adjusted for null, then reads error directly.

Fig. 3 shows one possible configuration of the error balancing and null-detector circuits. While simple in conception, this circuit requires extreme care in wiring layout, shielding and grounding practice, and the use of the finest components. Pick-up and stray capacitive loading must be kept to an absolute minimum. The basic accuracy of the error balancing circuit is not of primary significance, since in itself it measures only error, and its own inaccuracies merely lead to second order errors.

A number of error balancing circuits in use today in both 60 cps and 400 cps circuits have been significantly improved through use of components originally designed for higher frequencies, and therefore properly shielded, with minimized stray capacitive and inductive effects. General Radio components, while generally somewhat more costly than apparently equivalent items of less sophisticated design, have proven repeatedly to lead to correctly operating, sensitive, pick-up free circuits with least engineering effort. In many instances, previously unsatisfactory circuitry performed to specifications directly upon the substitution of a General Radio component. General Radio shielded resistance decade boxes have been found excellent in the standardizing circuits. Fig. 4 shows the output portion of the error balancing circuit and the correct grounding of the null transformer. Stray capacitance loading on the transducer must be accounted for in the circuit arrangement as indicated on the figure.

The null detector must be capable of distinguishing between the fundamental and harmonic error voltages. Frequently the noise-to-signal ratio in the vicinity of null is several hundred to one. Often noise is generated by the mechanical devices driving or actuating the transducer. Phase sensitive null detectors simplify the nulling of in-phase and quadrative error components. Fig. 5 shows null detector arrangement based upon a notch network in the feedback loop of a high gain amplifier. Fig. 6 shows a recently developed null detector of exceptional simplicity, with extremely high sensitivity to the fundamental null components.

Although this article makes no effort to survey or compare available varieties of test devices, we can say that probably the best known source of

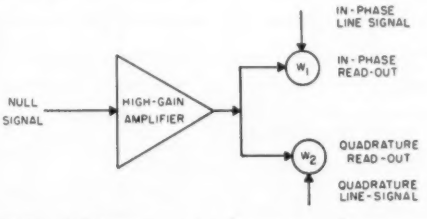

FIG. 6 Novel null detectors for extreme rejection of unwanted frequency components. W_1 and W_2 are center-scale wattmeters energized from the in-phase and quadrature line respectively. Meters of this type have two input coils, and only indicate the common-frequency components. This arrangement is extremely sensitive to small signal ratio null voltages.

voltage ratio standards is the Gertsch Products Co. of Los Angeles, California. A very popular phase sensitive, noise rejecting null detector is the Phasor, by Industrial Test Equipment Co. of New York City. There are, however, a great many alternative devices or equivalents on the market.

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The new units prototype was operated with a 28-foot parabolic reflector in 1957 to accomplish the first successful detection of Saturn and planetary nebulae as radio sources.

The receiver incorporates these key characteristics:

- remotely controlled noise balancing for discrimination against background-sky radiation and atmospheric capacity effects.
- remotely controlled calibration signal source
- automatic interlock and control panel for the protection of the low noise travelling-wave tube
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DESIGN TIME SAVER

THERMISTOR COORDINATES

Thermistor resistance versus temperature characteristics appear as a *straight line* when plotted on the special set of coordinates in the adjacent figure. This provides an especially convenient means for determining the basic parameters of a thermistor, and is also of use in devising thermistor networks for temperature compensation.

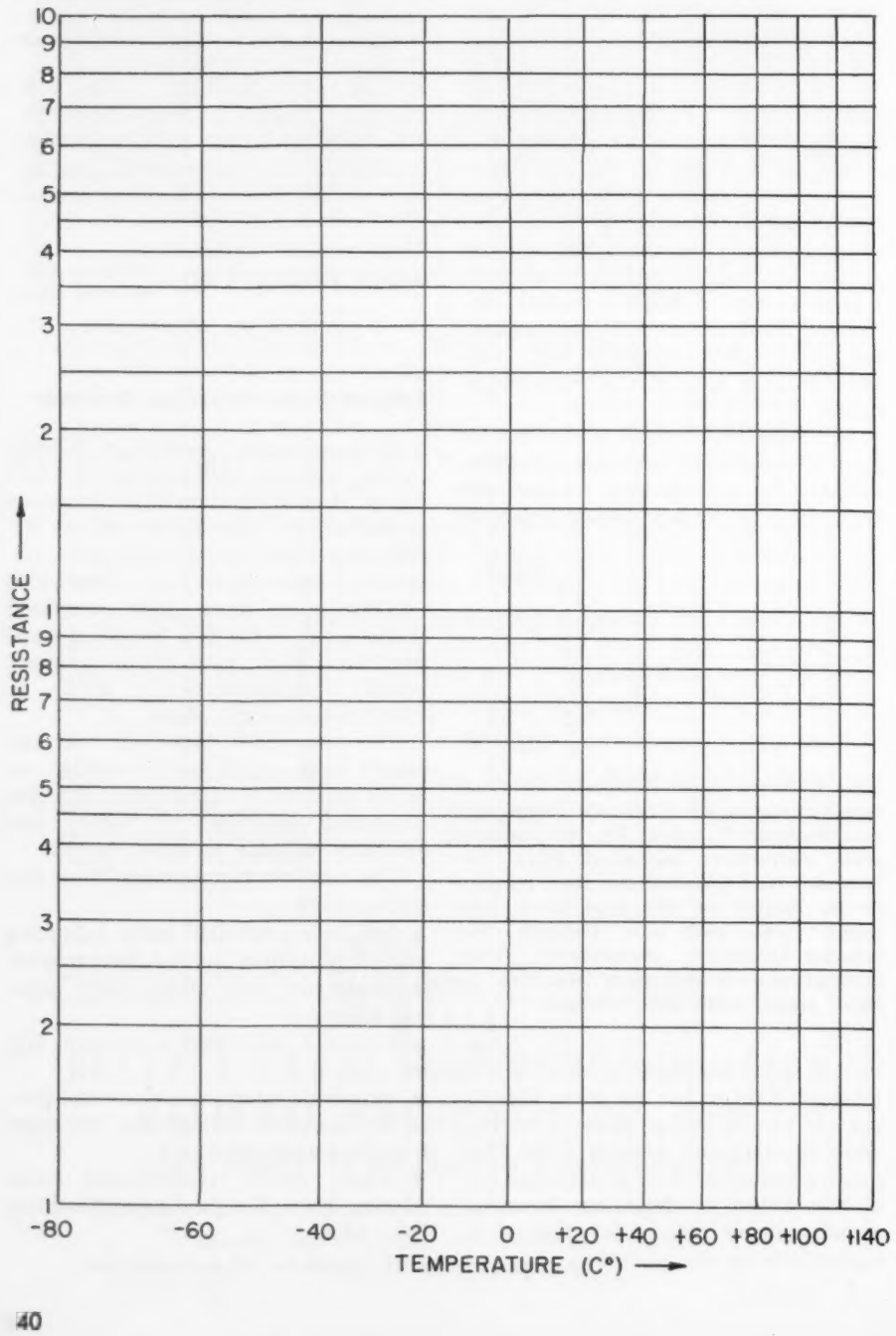
The coordinate system is based upon the well-known equation for the temperature characteristic:

$$R_T = R_o \exp [-B/T]$$

when R_T = ohms at absolute temperature T, and R_o and B are constant.

$$\log_e R_2 = \log_e R_o - B/T$$

If $\log_e R_2$ is plotted versus 1/T a straight line resistance versus temperature characteristic results, as represented on the coordinate.



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Heavy Duty Limit Switch

16-page catalog covering a complete line of heavy duty limit switches, gives complete details of three types–the plug-in "200LS" series, featuring quick replaceability; the compact "LS" series; and the rugged "ML" switches, available in regular or explosion-proof types. The catalog lists switches with a variety of contact arrangements, for either d-c or a-c applications. Several actuator designs in each switch type are shown.

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Fourteen Men In A Box

Illustrated booklet describes new approach to problem of checking complex electronic systems. By means of red and green lights, an automatic electronic tester denotes whether the equipment is operating properly. Included in booklet is a humorous presentation of equipment checkout problems and their solution.

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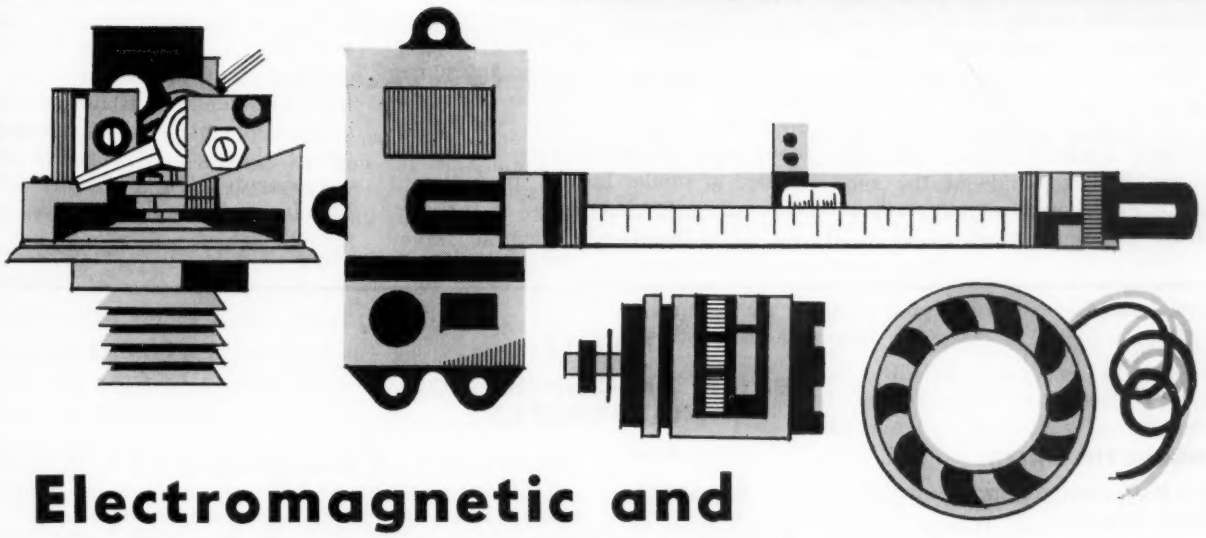
COMPONENTS DIGEST NO. 3



Electromagnetic and Potentiometer Transducers

MAGNETIC AND RESISTIVE PICKOFFS

Components Digest 3 deals with transducers for converting small linear or angular motions to electrical signals. The subject is limited to analog devices that require relatively small actuating forces or torques. Such devices are frequently referred to as "pick-offs."

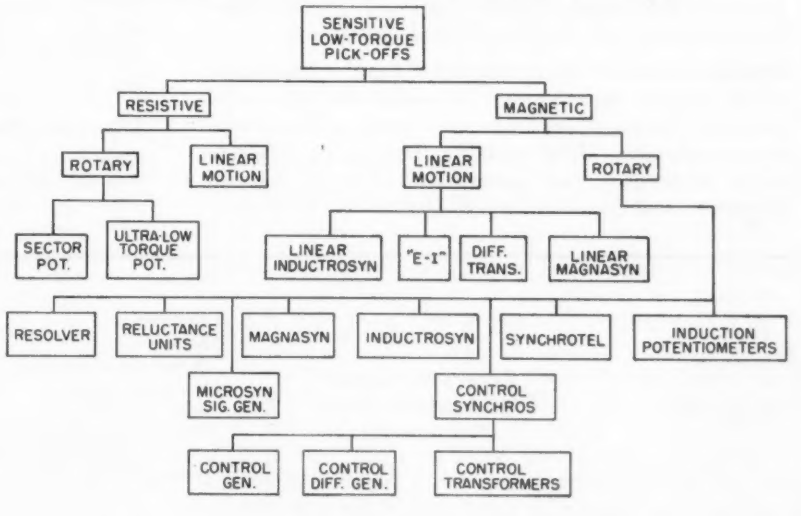
Pickoffs may be divided into two categories, resistive and magnetic. In resistive pickoffs, a slider or wiper moves along a resistance element varying the point of contact. The voltage developed from the point of contact to either terminal of the resistance element is a function of the slider position. Magnetic pick-offs, on the other hand, utilize an alternating magnetic field with position sensitive coupling to a secondary or output winding.

Pick-offs are frequently combined with additional transducers such as a spring-mounted mass, or a bellows assembly, to constitute an accelerometer or a pressure transducer respectively, for example. The greatest variety of combinations of pick-off and additional transducing element are possible. Although this presentation considers the performance specifications of a number of transducer types, it is primarily concerned with the behavior of the pick-off itself. Once understood, it is easy to combine the pick-off with the additional transducer elements required to perform some specific function. Excellent mechanical design is required to package high performance combinations to achieve required performance.

Table 1.1 is a master diagram showing the family of pick-offs covered in this Components Digest. The basic division, as indicated above, is between resistance and magnetic type components, each of which may be further subdivided into linear and rotary motion elements. Table 1.2 presents a compact easy reference summary or description of the nature of the de-

TABLE 1.1

CLASSIFICATION OF PICKOFFS OR SMALL DISPLACEMENT SENSING ELEMENTS



vices listed in Table 1.1. Table 1.3 defines essential performance and selection factors as suggested by Giannini. These tables will be useful in making an initial transducer selection for a particular application. Direct contact with a manufacturer, with the aid of the Buyers' Guide at the end of this Digest, should permit verification of the selection factors.

Transducer Characteristics

In addition to considering the general performance factors in transducer selection, it is necessary to define the errors in an exact fashion. Fortunately, many types of transducers can be described in similar fashion, permitting a more compact description of their errors. It is therefore efficient to survey the types of transducers in tabular fashion in discussing nonideal performance factors, as in Table 1.4. The individual transducers are more carefully considered in a later section.

Environmental factors are not considered here since a special issue of Components Digest, scheduled for March (next month), surveys environmental factors.

TABLE 1.2

BRIEF DESCRIPTION OF TRANSDUCERS

MAGNETIC UNITS

E-I Pick-off: *Assembly of transformer-like laminations whose output coils develop a voltage proportional to the displacement of a magnetic element from neutral position. Available for limited rotary as well as angular travel.*

Differential Transformer: *Similar to E-I pick-off, but designed to use cylindrical elements. A magnetic core is axially displaced, generating dissymmetry in two output coils, and net output voltage. Available for limited rotary as well as angular travel.*

Linear Magnesyn: *Proprietary item. Converts a linear displacement to a set of 3 voltages which may be applied to a rotary output device which develops an equivalent angle.*

Resolvers: *Rotary component designed for vector operations. Output voltage (s) vary as sinusoidal function of input voltage (s). Useful as very precise rotary displacement transducer.*

Synchro Control Generator: *Rotary component for transforming shaft angle to corresponding set of electrical signals for ultimate re-transformation to shaft position in remote location. Usually used with Synchro-Control Differential Generator and Synchro-Control Transformer.*

Synchro-Control Differential Generator: *Rotary component for modifying synchro-control generator output signals to correspond to addition or subtraction from generator shaft angle. Usually used with Synchro Control Generator and Synchro-Control Transducer.*

Synchro-Control Transformer: *Rotary component which accepts signals from generator or differential generator for reconversion to shaft angle with aid of a servo-mechanism. Often used by itself as an angle to signal transducer, but usually with Synchro Control Generator and Synchro-Control Differential Generator.*

Reluctance Unit, Rotary Differential Transformer: *Angular position pick-off with no electrical connection to rotor, operates by reluctance, many varieties.*

Inductosyn: *Proprietary product of Farrand Controls, Inc. Extremely precise transducer based upon magnetic circuit of conductors deposited on glass for stability, and operated at relatively high frequency. Extremely accurate. Required much auxiliary equipment.*

Magnesyn: *Proprietary product of Bendix. Used as angle transmission system where very low driving force is required. Based upon nonlinear properties of iron.*

Synchrotel: *Proprietary product of Kollsman Instrument Corp. For angle transmission where very low driving force is required.*

Microsyn: *Precise and sensitive pick-off device for converting angular displacement within a small range, to electrical signal. No rotor contacts. Very low reaction torque.*

Pancake-type Synchros and Pick-off Evils: *Specialized magnetic type of pick-off of various shapes and arrangements for incorporation in transducer devices.*

RESISTIVE UNITS

Linear Motion Potentiometer: *Resistance potentiometer with linear slider motion.*

Sector Potentiometer: *Portion of potentiometer resistance element used where total angular travel is limited. Frequently built into equipment in integral fashion.*

Ultra-low Torque Potentiometer: *Potentiometer designed to be driven by low force transducers. Use low contact pressures, frequently jewel bearings. Contact noise and vibration are problems.*

TABLE 1.4 | **Errors Of Linear Or Angular Type Transducers**

Resistive	*Magnetic*
Resolution	*Reaction torque*
Output loading errors	*Nonlinear or poor conformity*
Non-linearity or poor conformity	*Variation in scale factor and phase angle with input voltage, frequency, and temperature.*
Trimming errors for accurate adjustment	*Shifts in axis as null position with input voltage and temperature.*
Starting friction	*Loading errors.*

TABLE 1.3

DISPLACEMENT TRANSDUCERS,

PERFORMANCE AND SELECTION FACTORS AS DEFINED BY GIANNINI

Acceleration Effect is the difference between the output value without acceleration and the output value measured during a specified steady state acceleration in a specified axis at any one input value.

Calibration is the tabulation of output values versus input values.

Calibration Curve is the plot of the calibration data.

Critical Damping is that damping force which provides the minimum response time with no overshoot.

Cross Talk in accelerometers is the difference between output values at any one input value caused by an acceleration acting in a plane perpendicular to the sensing axis.

Damping Ratios given for certain instruments in this catalog are defined as the ratio of damping provided to critical damping. In other words, the damping ratio is actually a fraction of the critical damping.

End Points are the output values for the minimum and maximum values of the range.

Hysteresis is the maximum difference between the output values for the same increasing and decreasing input values. Input is the quantity-being-measured. It may be pressure, airspeed, altitude, acceleration, displacement, etc.

Linearity is the maximum difference in output between a calibration curve taken on increasing readings and the most favorable straight line.

Most Favorable Straight Line is the line drawn through the points of a calibration curve such that the distances from the line to a minimum of three most distant points is equal.

Output is the transformed quantity of input. It may be voltage, (AC or DC), voltage-ratio, resistance, resistance-ratio, capacitance, etc.

Range is the nominal extent of input variation measured by the instrument.

Repeatability is the difference between any single output value and the mean output value obtained from repeated tests under specified conditions for any one input value.

Resolution is the smallest change in input which will give a discernible change in output, IN THE ABSENCE OF FRICTION. In potentiomet instruments this is usually expressed in wires.

SCALE FACTOR is the ratio of full scale output to full scale input.

Temperature Effect is the difference between the output value at room temperature and at any other specified temperature at any one input value.

Threshold Sensitivity is the smallest change in input which will give a discernible change in output.

Vibration Effect is a measure of the peak instantaneous change in output value during the specified frequency of vibration at any one input value. Since average change in brush position does not exceed one wire, the DC voltage change is insignificant except at very low frequencies due to the slow response time of the system or associated equipment.

MAGNETIC TRANSDUCERS, Basic Theory

Magnetic transducers are defined for the sake of this presentation as those that convert a mechanical displacement into an electrical signal by a variation in mutual inductance between a primary (excited) winding and one or more secondaries. Before describing specific varieties, we will examine certain underlying principles, applicable to all.

Fig. 2.1 shows a pair of mutually coupled coils, one of which is energized, generating an output voltage in the other. The coefficient of mutual inductance is varied as a function of a mechanical displacement. The individual coil parameters are indicated on the figure.

The fundamental equations of the circuit of Fig. 2.1 for steady-state sinusoidal excitation are:

$$E_1 = (R_1 + j\omega L_1)I_1 - j\omega M_{12}I_2$$
$$O = -j\omega M_{12}I_1 + (R_2 + j\omega L_2 + Z_L)I_2$$
$$E_2 = Z_L I_2$$

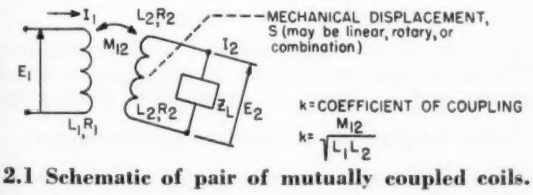


Fig. 2.1 Schematic of pair of mutually coupled coils.

These equations may be solved by conventional circuit theory:

$$I_1 = [E_1/Z_1 + (X^2_M/Z'_2)]$$
$$I_2 = [(E_1/Z_1)jX_M/Z'_2 + (X^2_M/Z_1)]$$
$$= jI_1X_M/[Z'_2 + (X^2_M/Z_1)]$$
$$E_2 = JI_1X_MZ_L/[Z'_2 + (X^2_M/Z_1)]$$

Where

$$Z_1 = R_1 + j\omega L_1$$
$$Z'_2 = R_2 + j\omega L_2 = Z_2 + Z_L$$
$$X_M = \omega M_{12}$$

Thus the primary current may be calculated as though an impedance XM_2/Z_2 were in series with the primary. The induced voltage in the secondary, corresponding to open circuit conditions, is jI_1X_M. Secondary current equals induced voltage divided by secondary impedance Z_2 plus $(XM^2/Z_1) \cdot (XM^2/Z_1)$ and XM_2/Z_2 are reflected impedances resulting from mutual coupling.

These equations represent the general approach to the solution of mutual inductance problems such as arise in transducer analysis. They may be readily extended to problems involving additional coils. They are most suited to

circuits where the coefficient of coupling is a small fraction, and where iron losses and saturation effects are negligible. For the important cases where these conditions do not hold, analysis is more conveniently carried out by equivalent circuit procedures described elsewhere in this Digest.

Magnetic Forces and Torques

Magnetic forces occur whenever the average energy of a magnetic field is changing, such as when inductance is varied as a function of mechanical displacement. The laws governing these relations are:

Forces on Circuit 1

$F_1 = I_1^2(dL_1/ds) + I_1I_2(dM_{12}/ds)$, for translation

$T_1 = I_1^2(dL_1/d\theta) + I_1I_2(dM_{12}/d\theta)$, for rotation

Force on Circuit 2

$F_2 = I_2^2(dL_2/ds) + I_1I_2(dM_{12}/ds)$, for translation

$T_2 = I_2^2(dL_2/d\theta) + I_1I_2(dM_{12}/d\theta)$, for rotation

Units

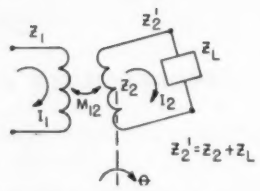
F = newtons
M, L = henries
D = meters
O = radians
I = amperes

In each instance, the derivatives are taken with respect to the displacement parameters corresponding to the displacement direction or torque axis.

By means of these equations the forces present in a great many magnetic transducers may be conveniently analyzed. A simplified or qualitative analysis is usually possible for the common magnetic devices where some of the derivatives may vanish or remain constant. In linear transducer for example, dM_{12}/ds and $dM_{12}/d\theta$ are constants, since M_{12} varies linearly with the independent variable. Where the secondary is unloaded, $I_2 = 0$ and the mutual inductance term vanishes altogether. In some devices, primary inductance is held constant as a consequence of the design of the magnetic circuit, and as a result, magnetic reaction force does not exist except as a result of dissymmetries arising from imperfect materials or manufacturing procedures.

Loading Capacitor-Effect on Magnetic Reaction

As a practical application of the above equations, consider a loaded linear transducer where mutual impedance varies with angular displacements, while primary and secondary inductance are constant. Fig. 2.2 illustrates this condition.



$T = |I_1 I_2|\,(dM_{12}/d\theta)\sin\theta$, where
$M_{12} = k_M\,\theta$
φ = time phase angle between I_1, I_2
$\therefore T = k_M I_1 I_2 \sin\varphi$, where by previous analysis,
$I_2 = j I_1 X_M/[Z'_2 + (X^2_M/Z_1)]$

Fig 2.2 Circuit relations for variable mutual inductance and constant primary and secondary inductances.

It is possible to adjust a load capacitance, and therefore Z_2 so that I_1 and I_2 are in time quadrature yielding no net reaction torque. The cancellation condition will vary depending upon the XM^2/Z_1 term. For lightly coupled circuits, however, torque reaction can be reduced to a negligible value over the whole operative range. For XM^2/Z_1 negligible, $I_2 = j(I_1X_M/Z_2')$. The required quadrature condition occurs for Z_2' real, or series resonance. More shifting more than 90 degrees actual negative torques may be generated which assist rather than oppose further transducer motion. In high Q circuits, carrier frequency shifts may reduce the value of this method of torque cancellation.

In more conventional applications, reaction torques for resistance or other loads may be similarly determined by direct application of the above theory.

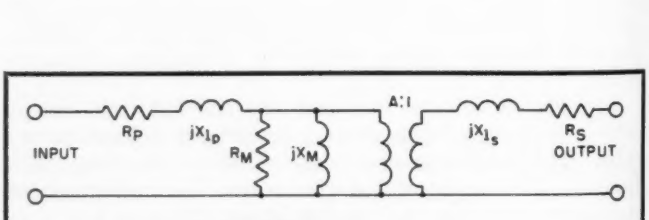
Secondary loading: Aside from the reaction torques considered above, loading of a transducer secondary can introduce additional variations. If the self inductance of the secondary winding is a function of shaft position, the loading will introduce errors in the output voltage versus displacement characteristic. Where a definite load is specified, it is sometimes feasible to provide load compensation by appropriate modification of the mutual inductance variation characteristic. This is commonly done with resistance potentiometer devices as described elsewhere in this Digest. Loading also modifies the output signal level and phase angle as a result of the voltage drops in the secondary impedance and reflected primary impedance due to load current.

TRANSDUCER EQUIVALENT CIRCUITS

It is convenient to eliminate the coefficient of coupling in the circuitry described above by substituting the more conventional transformer equivalent circuit. This permits direct analysis of the variables affecting performance as well as correlation with the transducer design parameters which determine its output and errors.

Fig 3.1 shows the equivalent circuit of a conventional transformer. By comparing it with the transformer sketch shown in the figure, you can relate the equivalent circuit constants to the magnetic fields and copper and iron losses of the transformer itself. This makes it easy to interpret the effect of changes in the transformer in relation to the equivalent circuit and performance. Thus if the d-c resistance of the primary winding were to increase with temperature, the resistance R_p of the equivalent circuit would change correspondingly. The effect of this change on transformer output is readily calculated.

Similarly, changes in the permeability of the magnetic



R_p = primary copper resistance
R_s = secondary copper resistance
R_M = resistance corresponding to core loss
X_M = reactance corresponding to mutual flux
A = primary to secondary turns ratio
$(X_l)_p$ = primary leakage flux reactance
$(X_l)_s$ = secondary leakage flux reactance

NOTE: Many of the approximations used in performance calculations of large transformers do not apply to miniature transducers, and the above circuits should be used as shown.

Fig 3.1 Equivalent circuit of a transformer.

material, or in the air gap dimension, affect X_M. The presence of a mass of ferrous material in the vicinity of the transformer modifies the leakage flux, changing the output scale factor. This simple point by point correspondence between equivalent circuit and actual device explains the popularity of the equivalent circuit method of calculation.

The next step is to adapt the conventional transformer equivalent circuit, somewhat modified if necessary, to the variety of transducers we are considering. If great sacrifice in the simplicity of the equivalent circuit is necessary to achieve an accurate representation, then the equivalent circuit should not be applied.

The most useful application of the equivalent circuit is to those devices in which input and output impedances are independent of mechanical input. Such devices include synchros and resolvers.

To represent a transducer by a static circuit, you have to specify a single arbitrary mechanical displacement selected for convenience. In an electrical resolver, the equivalent circuit corresponds to maximum coupling between a primary and a secondary winding. Standard transformer theory applies well here since the resolver primary and secondary constitute a moderately well coupled transformer for the maximum coupling position. For this position, it is easy to calculate the output scale factor and phase shift. Variation of these quantities with temperature, frequency drift, output loading or other pertiment operating conditions is readily calculated. For other angular positions of the driving shaft, the output voltage follows the prescribed law for the device. Variation of output with shaft position for a resolver is sinusoidal, the character of the sine wave being relatively insensitive to changes such as those above. For example, resolver output 30 degrees from a null position equals the output at maximum coupling as determined from the equivalent circuit multiplied by the sine of 30 degrees. The output function may be affected by loading in those devices where output impedance varies with mechanical displacement.

The foregoing shows the suitability of the equivalent circuit for analysis of effects of changing operating conditions upon transducer performance. Such changes arise either as a result of changing environments, or from practical circuit adjustment limitations. For example, you can't avoid some stray capacitance across the output of the transducer. Stray capacitance in a high impedance output circuit affects the magnitude and phase angle.

A similar though somewhat more complex situation exists for the synchro. Input and output impedances in a balanced synchro system are constant. Flux fields, power dissipation, scale factors and such possess a uniformity with shaft angle. These statements require mathematical justification, but for our purposes, we may accept their validity. We may therefore apply the equivalent circuit for an arbitrary shaft position, with convenience as the criterion.

As standard practice for synchros, the S1 and S3 leads (standard terminal designations) are tied together and voltages are applied between the combination and the remaining S2 lead. The R1, R2 leads are taken as a second pair of terminals. The shaft is set for maximum coupling, establishing the equivalent circuit condition as for a resolver. For a synchro differential having three rotor terminals, the R1, R3 terminals are tied together and the pair energized with respect to the remaining R2 lead prior to setting at maximum coupling.

The equivalent circuit may be determined either by direct measurement or indirectly from data provided by the manufacturer. Depending upon the nature of the data and the detail and accuracy of its presentation, the equivalent circuit may be derived more or less accurately. Many manufacturers now tabulate the important synchro impedances such as the open and short circuit impedances on the input and output windings.

Equivalent circuits may be adapted with some loss of generality to the case where input impedance is constant while output impedance varies with shaft position. Such devices include many important transducers such as the induction potentiometer. For this type device the variation of output impedance with shaft position affects the linearity or conformity when any appreciable load current is drawn. However, as described elsewhere in this Digest, compensation for specific load errors can be included directly in the design to provide required accuracy. However, as with the resolver, it is important to specify scale factor and phase angle, and here again an arbitrary position is chosen.

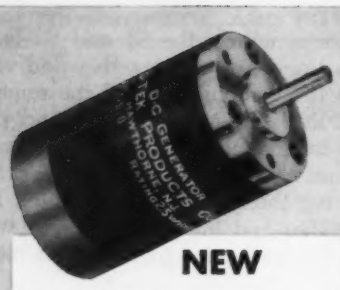
For limited range devices such as the E1 pickoff, differential transformer or induction potentiometer, the output displacement point for accurate performance is generally specified. At this point an equivalent circuit may be drawn. Because of the non-constant output impedance, these circuits are accurate only for light loads. Their principle value is in the investigation of primary circuit conditions which affect the internal flux field and therefore the scale factor and phase shift of the output voltage.

As discussed elsewhere in this Digest, many devices such as the induction potentiometer incorporate additional short circuited windings displaced 90 degrees from the primary for zero mutual coupling. These windings lower the high points of the output impedance, providing greater uniformity. If the output function is designed to provide accuracy for a specified load condition, then some average figure for output impedance would be useful in determining the affects of additional or incorrect loading. Thus, where output impedance ranges between 500 and 700 ohms, and something like 600 ohms is the assumed average, the affect on scale factor and phase shift, say of a 1000 micromicrofared capacitance across the output, can be readily calculated. This capacitance, however, also affects the angular accuracy because of the changing output impedance.

EFFECT OF SMALL CIRCUIT CHANGES ON PERFORMANCE

In setting necessary circuit adjustment tolerances, ability to determine transducer errors introduced by small changes in the circuit parameters is convenient. For example, some resistance in wiring supplying the transducer primary, or stray capacitance across the output winding, can cause significant errors when high accuracy is required. Fortunately, we can calculate such errors easily with the aid of the network theorems of elementary a-c circuits. These theorems are:

- When an impedance is inserted in a line previously carrying a current I, the impedance may be replaced by a voltage source opposing the flow of current and having a magnitude equal to I times the value of impedance.
- When an impedance is placed across a line having a voltage V prior to its insertion, then the impedance may be replaced by a current source drawing a current from the line equal to V divided by the magnitude of the impedance.



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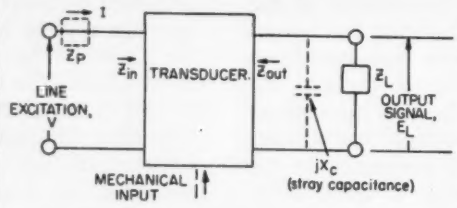


Z_{IN} = input impedance
Z_{OUT} = output impedance
Z_p = impedance inserted in primary

Mathematical analysis

Effect of inserted impedance

$V - Z_p I = V$, new effective primary voltage

$I = V/Z_{IN}$

$\therefore V' = V - (Z_p/Z_{IN})\ V = V\ (1 - Z_p/Z_{IN})$

The new current, I', is easily obtained—

$I' = V/Z_{IN}\ (1 - Z_p/Z_{IN}) = I(1 - Z_p/Z_{IN})$

The new output voltage, depending on input current is

$E'_L = E_L(1 - Z_p/Z_{IN})$

The new current and output voltage are easily calculated by the above formula. The power input ratio is

$P'/P = |\,[1-(Z_p/Z_{IN})\,]\,|^2 \sim |\,1 - (2Z_p/Z_{IN})\,|$

for small Z_p

Effect of stray load capacitance

The secondary stray capacitance may be replaced by a current source pulling a secondary current of

$I_{(\text{stray capacitance})} = E_L/-jX_c = j(E_L/X_c)$

The change in output voltage will be $jZ_{OUT}(E_L/X_c)$, which may be considered as an error due to stray capacative loading.

Fig 4.1 Generalized transducer circuit, effect of small circuit changes.

The advantage of employing these theorems is that we replace the inserted impedances, whether in series or across a line, with corresponding voltage or current sources. Then, by applying the principle of superposition, the errors may be calculated directly as the changes in output resulting from the inserted voltage or current source. Since these theorems may be commonly applied to calculate the errors introduced by small circuit changes, approximate calculations often suffice to give adequate answers.

Consider as an example the general transducer circuit of Fig. 4.1. Let us calculate, as two separate phases of the problem, the effect of inserting an impedance in the line of the input, and the effect of adding an additional stray capacitance $-jX_c$ across the output.

In the first instance the added impedance acts as a voltage opposite in direction to the input voltage and having a magnitude of I times Z_{IN}. Since the output of the transducer depends upon input current rather than input voltage, we only need to calculate the change in input current resulting from the added voltage source to find output change due to the series impedance. Similarly, knowing the new current, as well as the change in circuit impedance, it is simple to determine the change in primary power consumption. Mathematics of the above approach, illustrated in detail to show the simplicity of the reasoning are included in Fig. 4.1.

Effect of output stray capacitance may be calculated using the second of the network theorems. The original

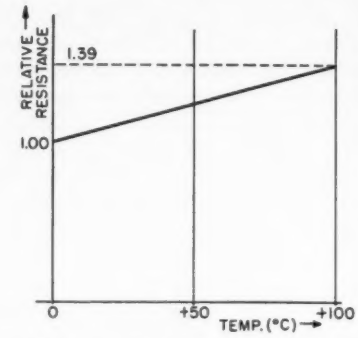
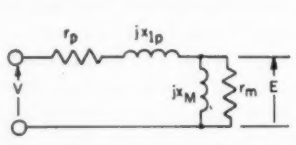


Fig 4.2 Variations of copper resistance with temperature.

output voltage is given. By the second network theorem, we replace the parallel capacitor with a current source having a magnitude equal to output voltage divided by the reactance of the capacitance, taking due account of the phase angle of the output. By superposition, we easily determine the changes in the behavior of the circuit. The figure shows how these calculations



r_p = primary d-c resistance
X_{1p} = reactance due to primary leakage flux
X_m = reactance due to primary main flux
r_m = resistance corresponding to core loss resulting from primary main flux
E = output voltage for 100% coupling and unity-turns ratio

Primary circuit representation of magnetic transducer

Approximately:

$$E/V = X_m/[(X_1)_p + X_m] = 1/[1 + (X_1)_p/X_m] \text{ phase lead} = r_p/[(X_1)_p + X_m] \quad \left.\begin{array}{l} \\ \\ \\ \end{array}\right\} \begin{array}{l} r_p(X_2)_p << X_m \\ \\ X_m << r_m \end{array}$$

Fig 4.3 Approximations for estimation of magnitude and phase errors.

are carried out illustrating how simple approximate methods may be applied in the determination of errors. It is far more difficult to determine errors as a result of small circuit changes by the

direct method of making complete calculations for both cases and taking the difference between two nearly equal quantities.

As an application of the above calcu-

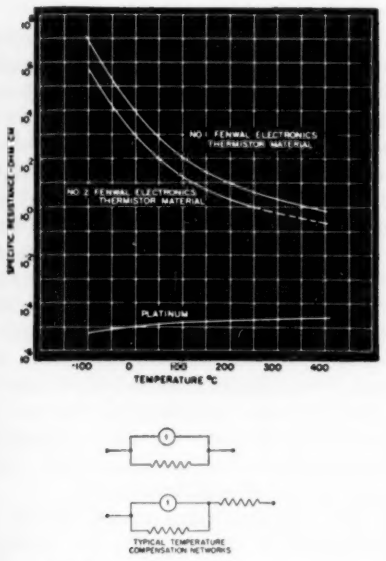


Fig 4.4 Characteristic temperature resistance curve for a Fenwall thermistor, and common network configurations.

lation procedure, it is easy to calculate errors due to changing temperature. Aside from changes in the mechanical structure as a result of coefficients of expansion of materials, fatigue and aging, the principle transducer error is

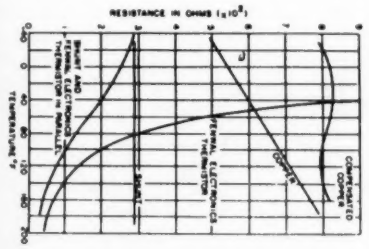
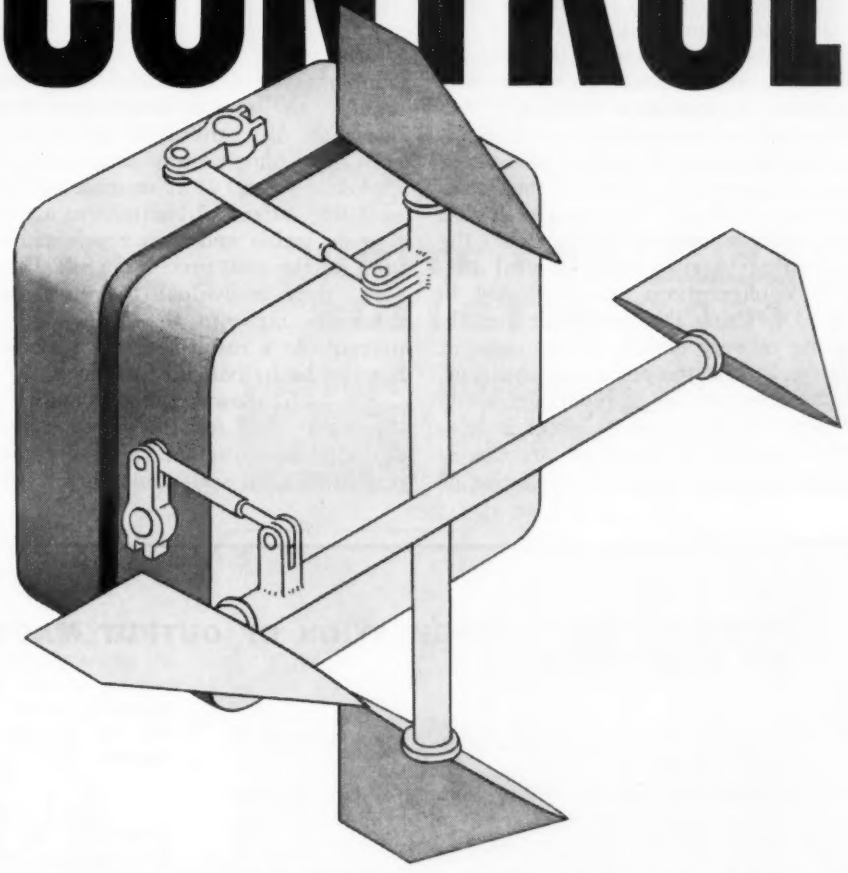


Fig 4.5 Compensation of copper resistor for temperature change using a Fenwal thermistor.

caused by changes in primary d-c resistance. Primary windings, made of temperature sensitive copper wire, and carrying significant power, change resistance as a function of temperature in accordance with the well known law shown in Fig.4.2. Since the secondary is usually very lightly loaded, secondary copper resistance changes are most often negligible. Where this is not the case however, calculations may be extended to include such changes.

If the d-c resistance of the transducer primary is known, a temperature change of about 50C will cause a corresponding change of about 20 percent in copper resistance. This additional resistance can be inserted in the pri-

MISSILE CONTROL



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mary winding just as in the worked-out problem above. If the primary is a relatively high Q reactor, then the effect of this resistance increment will be primarily to change the phase of the transducer output. If the primary impedance is resistive, then the effect will be to cut the magnitude of the output voltage. Figure 4.3 extends the technique of Fig. 4.1 to include approximations for estimating magnitude and phase errors very quickly for cases where the approximations apply.

Thermistors are frequently used for temperature compensation. These are negative temperature coefficient resistors whose temperature coefficient is many times that of copper. However, they are decidedly unlinear; their temperature coefficient decreases at higher temperatures. Characteristics of the thermistor together with typical network configurations are illustrated in Fig. 4.4. Using the thermistor directly results in very serious errors since at extremely low temperatures, the thermistor goes way up in resistance, while at high temperatures its effect is relatively negligible. Common practice is to devise simple networks consisting of

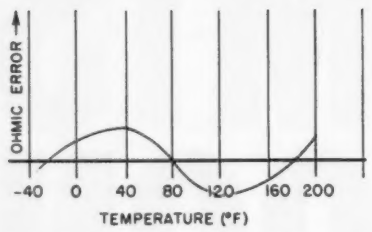

Fig 4.6 Errors in compensation resulting from curvature of thermistor characteristic.

combinations of thermistors and fixed resistors to provide temperature compensation. By careful design of these networks, temperature errors are reduced by factors of 10 or more without excessive difficulty. Thermistors are extremely stable and as a result can be used for the most precise circuits. However, their individual tolerances are relatively high, in the order of ±5 percent. As a result thermistor circuits have to be individually trimmed.

Fig. 4.5 shows a combination of thermistors and resistors used to compensate one particular value of copper resistance. The approximation of compensation results from curvature of the thermistor and inability to provide more than a reasonable fit of required and actual characteristics.

Since the thermistor is amenadable to straightforward mathematical calculation, a given thermistor circuit may be calculated and the errors due to the curvature may be plotted roughly as shown in Fig. 4.6. These errors represent ohms deviation of required and actual characteristics. By inserting these ohms in the basic equations, of Fig. 4.1, we can determine the transducer error resulting from imperfect compensation by the thermistor. This approach is simple and straightforward and permits the determination of thermistor tolerance and selection of resistors. As a matter of fact, the entire approach indicated in this section is very valuable in specifying tolerances.

The above circuit equations can be extended to cover cases of changing line frequency, variations in manufacturing tolerances, such as in the airgap that determines sensitivity, stability and the input impedance, as well as the allowable tolerances in resistance of all the windings.

TEMPERATURE COMPENSATION OF OUTPUT MAGNITUDE OF A TRANSDUCER

Consider the equivalent output of a transducer shown in Fig. 5.1 below.

The open circuit output voltage is E_o', and the output impedance is Z_o. An output network consisting of two temperature sensitive elements, R_1 and R_2 is used to compensate for variations in E_o' with temperature. Since final compensation must be made on an actual unit, the determination of compensation circuit requirements may be carried out by simple approximations. Assume for this example:

(1) That only magnitude compensation is required.

(2) That R_1 plus R_2 constitute a sufficiently light load so as to permit us to neglect Z_o.

The voltage division ratio of the output circuit is given by:

$$k = R_2/(R_1 + R_2)$$

Take differentials to determine the variation of k with R_1 and R_2. Reduce the differentials to a form where values are given on a per unit basis.

$$dk/k = (I - k)[(dR_2/R_2) - (dR_1/R_1)]$$

This fundamental formula relates the percent change in transmission ratio to the individual percent in the R_1 and R_2 resistors.

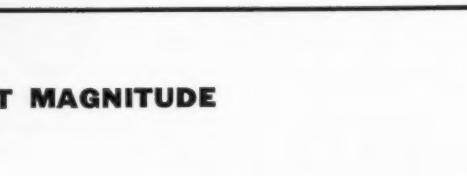

Fig 5.1 Transducer equivalent output circuit for compensation problem.

As an example, assume $k = 0.6$. If the known variation in k over a temperature range is 16 percent, then

$$0.16 = 4.0[(dR_2/R_2) - (dR_1/R_1)]$$

$$(dR_2/R_2) - (dR_1/R_1) = 0.4$$

If R_2 is a positive temperature coefficient resistor, and R_1 a negative temperature coefficient resistor, then the sign of (dR_2/R_1) reverses:

$$(dR_1/R_1) + (dR_2/R_2) = 0.4$$

The sum of the percent changes in the individual resistors must equal 0.4 for the particular range of temperature.

INDUCTIVE PICK-OFFS

Where very low friction and limited angular or linear travel are required, simple pick-off devices such as shown in Fig. 6.1 may be employed. These devices are commonly made up of E-shaped transformer laminations with windings on the three legs arranged as shown in the figure. Normally, the center coil is exited by an a-c voltage and the two outer coils are connected so that with the armature in the center of null position, their induced voltages cancel. When the position of the armature is diplaced from null, the flux generated in the center leg is no longer equally distributed between the two outer legs, but increases in the leg toward which the armature moves. As a result of the unbalancing of fluxes in the outer legs, the balanced position is upset and voltage is generated in the output coils approximately proportional to the magnitude of armature motion. As the armature passes through the null position, the output voltage undergoes a 180 degree phase reversal, a necessary condition for operation in a null-seeking servomechanism.

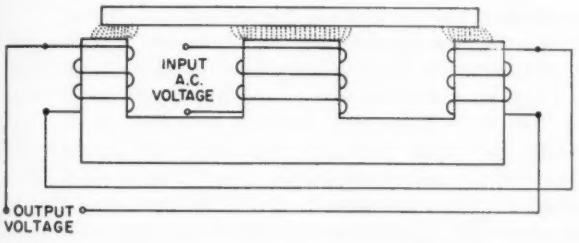

Fig 6.1 E-I Pickoff at null position. Main air-gap fluxes and fringing fluxes are shown. The fringing flux paths do not change for small displacements in the vicinity of the null. Consequently, for the assumption of ideal geometry and negligible iron reluctance, the reluctance of the primary circuit is constant, indicating zero reaction torque.

Some design features of a good pick-off are illustrated in Fig 6.1. To achieve good linearity of output voltage with armature displacement, you have to control geometric tolerances closely. Lamination material with high permeability, such as Mumetal, minimizes nonlinearities and harmonics introduced by the iron. A similar effect is achieved by using a fairly large air-gap which at the same time reduces the sensitivity to slight mechanical misalignments. When length of the armature is equal to distance between the center lines of the outer legs, you can minimize reluctance forces or torques exerted by the magnetic circuit on the armature, and at the same time, maintain a reasonable range of linear motion. Reaction force on the armature is given by the formula: $T \alpha I^2(dL/ds)$, where I is the current in the center coil, and dL/ds is the rate of change of self-inductance with mechanical displacement.

Fig 6.1 indicates that if we neglect iron reluctance, the total reluctance as seen from the center leg is independent of armature position as long as the fringing flux paths are not modified by armature displacement. That is, for a limited range of motion, fringing fluxes are unchanged as a result of armature movement, total reluctance is constant, inductance is independent of armature position, and there will be no reaction torque. Similarly, reluctance of the outer legs varies in linear fashion with armature displace-

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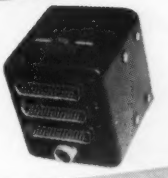

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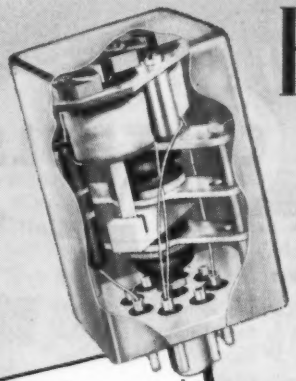

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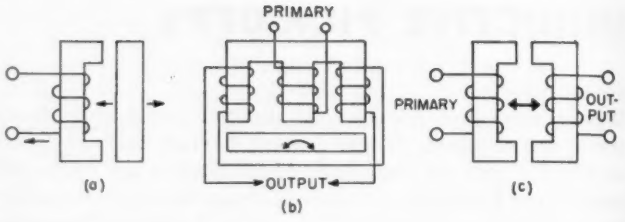


Fig. 6.2 Pickoffs whose operation depends on varying the air-gap reluctance.

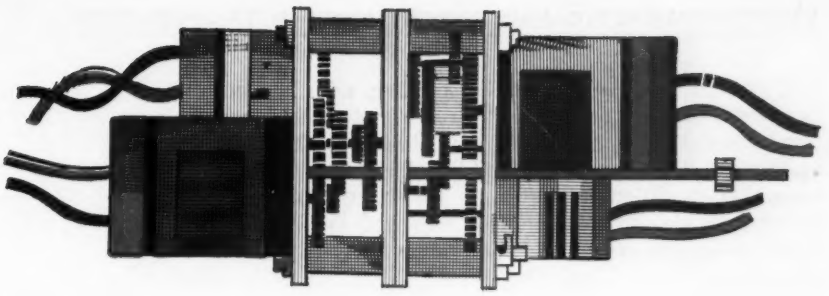
ment, the necessary condition for a linear output voltage function of armature displacement. This particular condition is of special importance because force must not disturb accuracy of the transducer whose output is being measured. However, where the transducer itself incorporates a restraining spring or its equivalent, any spring-like reaction torque of the pick-off might be considered as part of the overall spring constant and its effect included in calibration of the system.

As in all inductance-type pick-offs, residual voltages appear in the output. These residual voltages consist of three components, one in phase with the normal generated output, one in time quadrature, and harmonics generated by iron nonlinearity. In-phase residual voltages appearing at null may be cancelled out either by a network energized from the a-c supply and suitably coupled to the output winding, or by a shift in armature zero position. This latter method, re-zeroing of the armature, is ideal for correcting for slight unbalances in the symmetry of the magnetic assembly. Quadrature residual voltage, on the other hand, cannot be cancelled out by zero shifting, but must require network trimming procedures. A suitable value of capacitor from one or the other primary lead to the ungrounded output lead may suffice to null out quadrature voltage. Many other networks, as well as more specialized techniques are employed.

Residual voltages tend to reduce sensitivity of a servo, introducing amplifier saturation and therefore reduction of gain with consequent loss of accuracy. Harmonic residual voltages are minimized by keeping the iron flux density low, using a large air gap, and specifying very high permeability nickel steels. Harmonics may be eliminated where necessary by using a band-pass filter adjusted to pass only fundamental frequency. However, such a filter could introduce servomechanism dynamic errors and care must be taken in its design.

Sensitivity is improved by reducing the air-gap to a minimum and shortening the armature so that in the null position it just barely touches the two outer legs. However, this reduces linearity and at the same time adds considerable magnetic reaction torque, making the mechanical set-up of this device particularly critical.

There are a great variety of inductive pick-offs. Fig 6.2 shows a number of pick-offs whose operation depends upon varying the air-gap reluctance. In these pick-offs, a distinct magnetic reaction force is exerted on the armature. Such devices can be used only when reaction is not objectionable. Reaction torque increases rapidly as the air-gap is reduced, and as a result it is possible in an improperly designed system to develop snap action such that the armature locks in the minimum air-gap position. Such circuits, however, when properly designed, provide very high sensitivity to small displacements.



Synchros

Synchros are motor-like devices used to translate angular position to electrical signals or vice-versa. Because of the fundamental nature of this operation and the ease with which it is performed by synchros, these devices are used very widely.

There are two essential types of synchros. The first of these, the simplest but least commonly used, is the group of *torque synchros* which can transmit angles directly without the use of additional servomechanism components. Where light loads are to be angularly driven, such as pointers and remote indicators, torque synchros are satisfactory. However, because angular error depends upon output shaft loading, they are inadequate for appreciable loads. Furthermore, their nature requires that they operate at high flux densities and quite hot, introducing angular inaccuracies. These units are not to be considered further in this text, since their application, strictly speaking, is not as transducers.

More important are the control synchros, including three basic types: the *synchro control generator*, the *control differential generator*, and the *control transformer*. These are interconnected by simple wiring, with electrical energy applied only at the input terminals to the synchro control generator. The synchro generator converts its shaft angle to a set of electrical voltages. The differential generator, energized by the synchro generator, has output windings which in turn, energize a control transformer. The shaft angle of the differential generator adds to, or subtracts from, the input shaft setting of the control generator. The control transformer receives signals from the generator or the differential generator and, by means of a servomechanism, is driven to a null depending upon the shaft position of generator and differential generator. The control transformer has a two terminal output which develops an error signal proportional to the sine of the angle of its shaft displacement from correspondence with generator and differential generator angles. This error is amplified to drive a servo motor which in turn drives the control transformer and any other additional load to a null position.

Control synchros are used with a servomechanism. Output energy is supplied by the servomechanism, permitting torque multiplication.

Fig 7.1 shows a typical angle transmision system incorporating a transmission generator, a differential generator, and a control transformer, as well as a servomechanism for driving the output angle. The figure indicates how this system works. Where required, additional control transformers can be connected to the generator or differential generator, or additional differential generators may be inserted in chains. A great variety of practical configurations may be assembled for specific use. Because of transient coupling as well as increased errors, torque synchros are seldom used with control synchros.

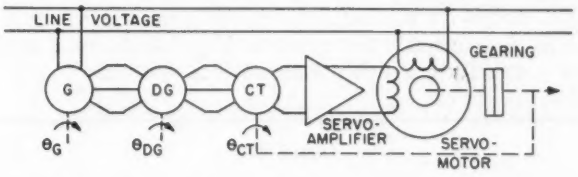


Fig 7.1 Synchro angle transmission system incorporating a synchro generator, differential generator, and synchro control transformer. The generator translates the line voltage excitation to a flux field whose orientation with respect to its three-phase secondary winding is determined by its shaft angle, θ_G. The single-phase field in the DG primary, which is the resultant of the three input currents may be re-oriented by adjustment of θ_{DG}. The CT is positioned to correspond to θ_G-θ_{DG} by the servo-system shown in the figure.

HOW SYNCHROS WORK

Although variations exist, Fig 7.2 shows the common arrangement of magnetic circuits within a synchro. The stator incorporates a three phase winding. (However, it should be remembered that only single phase line power is applied.) The generator rotor may be a salient pole or conventional wound rotor, incorporating a single phase winding. Sometimes a short-circuited winding is applied at tight angles to the main rotor winding to improve accuracy. However, its role is not fundamental and it will not be considered here further.

The differential generator has a three phase stator winding and a three phase rotor winding. It is distinguished from both the generator and the control transformer by the

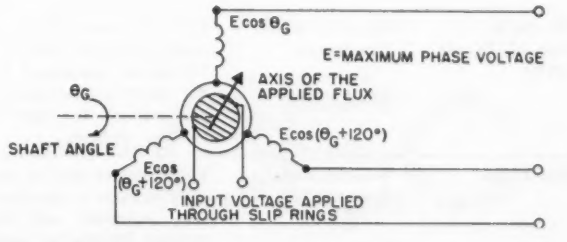


Fig 7.2 Simplified diagram showing how the input voltage applied to the rotor winding of a synchro generator induces secondary voltages in the three-phase output winding which vary sinusoidally with shaft position.

3 slip rings necessary to make coupling with the output brushes. Windings are arrayed on the motor-like magnetic lamination stacks generating fields similar to those shown in Fig 7.2. This figure, in simplified form, shows the ideal operating condition in a synchro transmission system. Because each synchro represents a balanced load, additional synchros on the system do not change the basic theory of operation.

Synchro Accuracy

Synchro accuracy is affected by design and manufacturing errors. Transmission accuracy can vary from about 5 to 30 minutes of angle, with instances of both better and worse accuracy occuring. Accuracy is generally improved in larger units, or units operating at higher frequency, such as 400 cycles rather than 60 cycles. The more important factors determining accuracy are the roundness and symmety of the magnetic circuit elements, and the uniformity and balance of the three-phase windings. Factors tending to produce unbalance or dissymetry introduce errors. Iron in the magnetic circuit is of highest importance, requiring use of high nickel alloys with very high permeability. These alloys are carefully annealed and assembled so as to eliminate strains or grain effects which tend to introduce dissymmetry.

Since the windings generate the magnetic fields, layout of the coils is extremely important. The choice of slot combination, turns per slot skew, and the shape of salient pole structures, are design factors affecting the sinusoidal flux distribution.

The nature of the angular error, particularly the frequency of repetition in a 360° period, is a function of its origin. Table 7.1 tabulates the errors occuring in a synchro system, indentifying the sources. Fig 7.3 shows a typical error curve for a synchro transmission system.

TABLE 7.1

ERROR COMPONENTS IN SYNCHRO TRANSMISSION SYSTEMS

The error pattern of a synchro-transmission system (error versus shaft position) may be analyzed into its Fourier Components. These will have a periodicity which may be expressed in cycles per complete synchro revolution. In general, the pattern of quadrature residual voltage will have a similar appearance, the relative magnitude being determined by the source of the error.

Error Comp.	Origin	Possible Cause
One cycle	Rotor eccentricity	Manufacturing inaccuracies, purely random.
Two cycle	Unbalance in 3-phase circuitry	Stray capacitance or resistance in line, elliptical stator air-gap, stray line coupling. Random occurrence.
Six cycle, also 12, 18, etc. cycles.	Non-sinusoidal flux waves.	Common error pattern in many synchros due to harmonies generated by the windings. Uniform error pattern for specific synchro designs.
Slot Errors	Non-sinusoidal flux-wave.	Error pattern due to slot combinations in synchros. Less important with increased number of slots. Minimized by proper skewing. Uniform error pattern for specific synchro designs.

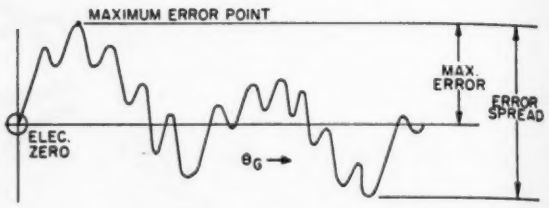


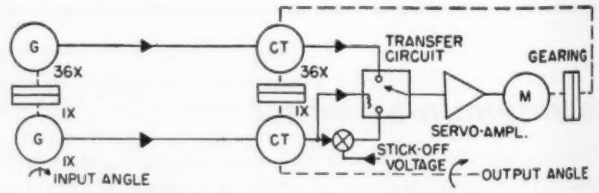
Fig 7.3 Typical error of synchro transmission system. For discussion of the composition of this error curve, see Table 7.1.

Two-Speed Synchro Systems

Frequently it is necessary to achieve angle transmission accuracies of the order of a fraction of a minute. To do this, a multi-speed synchro system is used. This type of synchro operation is described elsewhere, for example, by Ahrendt in "Servomechanism Practice". Fig. 7.4 shows the arrangement of a multi-speed system and lists the steps in setting up. Accuracies are limited primarily by the gearing. Well under one minute accuracy is frequently achieved for long distance transmision even in the face of severe environments and nonideal operating conditions.

Velocity Errors

In addition to the static errors discussed above, synchros are subject to an error due to rotational velocity. Thus, if the rotors of a generator and control transformer are aligned to produce essentially zero error output, and if the rotors are then rigidly coupled together, so that there can be no relative motion between them, and if then the two synchros are rotated together, a voltage will appear at the control transformer terminals. This voltage will consist in part of components due to the static errors discussed before, but there is also a steady component that increases with speed. Hence, if the two synchros are used in a servo system that tends to null the in-phase component of the output voltage, the output tends to run slightly behind the input when a constant velocity input signal is applied. This velocity error is in addition to the error normally found in servo systems having velocity lag. These output errors occur in the high-speed synchros of a multi-speed synchro system. They are significant when the synchro system is going above about 1/3 of synchronous speed.



X number indicates relative shaft speed.

Fig 7.4 Two-speed synchro system, simplified diagram. Ratio of 36:1 is commonly used and convenient, but other values may also be used. The purpose of the 1-speed channel is to avoid output angle ambiguity by insuring that the output angle is approximately correct. If the 1 × CT goes too far from null, it energizes the transfer circuit, connecting the 1 × CT into the servomechanism, which drives back to the vicinity of null, where the 36 × CT takes over. Stick-off voltage is used where the speed ratio is even to avoid an ambiguous 180 degree null point. More specialized references should be checked for further information.

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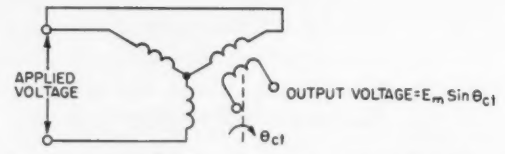
The Synchro as a Transducer

The above material describes the synchro in its most widely used form as an angle transmission device. Used in sets or chains, it provides extreme versatility for transmission of data between sub-sections of a major system. Accuracies are sufficient for precise requirements. We propose now to examine the synchro control transformer when used as a transducer for the measurement of small angular displacements.

Fig. 7.5 shows a control transformer used as a transducer. A single-phase voltage is applied to the primary winding, and an output voltage is taken from the secondary, depending upon its angular position. The voltages shown in Fig 7.5 correspond to the standard Bureau of Ordnance voltages for 115-volt synchro systems.

Ideally, the voltage applied as in Fig 7.5 results in a sinusoidal distribution of line-frequency alternating flux around the air-gap. Displacing the rotor from null results in an output voltage, which for small displacements is approximately linear. For improved linearity, it is necessary to re-distribute the windings in a special manner to achieve a different flux pattern, resulting in a linear rather than a sinusoidal output function.



E_m=Maximum CT output voltage at given applied voltage

Fig 7.5 Control transformer used as a transducer. Output voltage varies sinusoidally with shaft displacement from null. For small angles, the relationship is linear to a good approximation. Output is smooth and free from resolution steps. The limitation for extremely small total angular travels (less than a half degree) is the drift of null position with temperature and aging, and residual voltages.

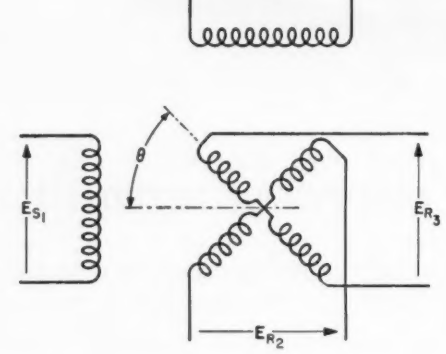
Notwithstanding the error due to the sinusoidal flux pattern the synchro as a limited range angle transducer is extremely popular, and can achieve very satisfactory performance. Synchros are available from many sources. The resolutionless output is suitable for measurement of extremely small angles. Synchros can operate at relatively high speeds, standard government units being rated at 1200 hours of life at 1500 rpm with no degradation of performance.

ELECTRICAL RESOLVERS

Electrical resolvers are small motor-like components in the same family as synchros. They differ from synchros in that they have two input windings and two output windings on the rotor and stator respectively. The windings on each member are distributed at right angles to one another so that individual rotor windings and stator windings do not interact among themselves. The resolver is represented schematically as shown in Fig. 8.1. The unit generally has four slip rings and brush assemblies providing electrical contact to rotor windings. For transducing applications, only one set of slip rings may be required, or, in many instances where angular travel is limited, pigtail connections may be provided.

When a resolver primary winding is excited, voltage is generated in the opposing windings, varying as a sinusoidal function of shaft position. Since the windings are distributed at 90 degrees to one another on both rotor or stator, output voltages constituting sine and cosine functions of shaft angle are generated. Simultaneous application of voltage to both primaries causes a resultant magnetic field whose magnitude corresponds to the square root of the sum of the squares of the separately applied voltages and whose angular orientation depends on the vector resultant of the separate applied voltage vectors. Because of these properties, a resolver is directly applicable to problems involving trigonometry, such as the conversion of coordinates, rotation of coordinates and in most computing applications where trigonometric functions appear. Resolvers are especially suited to fire-control problems in which a good deal of the computation is necessarily based upon trigonometry. Here, however, we will not consider these applications of the resolver, but rather its use as a transducing element.

Many variations of the resolver exist. Resolvers may serve as four-wire synchro systems where accuracies of the order of several minutes are required. Large diameter units, having many poles, which can be regarded either as resolvers or synchros, sometimes called "pancake units", are frequently found as transducer-type pickoffs. Sixty-



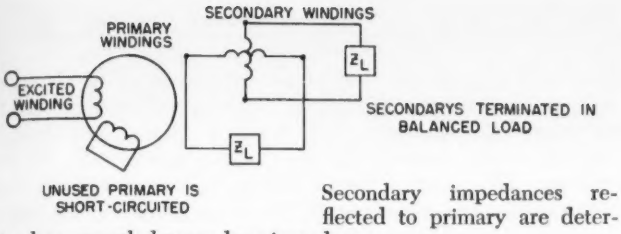
INPUTS	OUTPUTS
E_{S_1}	$E_{R_3} = E_{S_2}\cos\theta - E_{S_1}\sin\theta$
E_{S_2}	$E_{R_2} = E_{S_1}\cos\theta + E_{S_2}\sin\theta$
θ	

Fig 8.1 Schematic representation of the electrical resolver.

cycle resolvers as well as 400-cycle resolvers are available, the former being considerably larger than the latter. Resolvers are also available for application up to many kilocycles.

Before proceeding to a detailed consideration of the resolver as a transducer, observe that when properly applied, the resolver, either by itself or as part of a transmission system, provides a constant input impedance at any excited windings, as well as a constant output impedance. The explanation is given in Fig. 8.2. In a specific simple instance, the output winding couples the energized input winding as well as the short-circuited winding at 90 degrees to the excited winding. The sum of the reflected impedances for sinusoidally constant varying coupling coefficients is constant, providing constant output impedance, as is easily proven by the previous theory. Thus the resolver is especially easy to use if care is taken to make sure that all circuits and loading are symmetrical and balanced.

The resolver is particularly well-suited to measurement of a limited angular travel. The absence of resolution steps



Secondary impedances reflected to primary are determined as: coupled secondary impedance

$$= X^2_m \sin^2 \theta/(Z_s + Z_L) \; + \; X_m^2 \cos^2 \theta/(Z_s + Z_L)$$

X_m = maximum mutual reactance to either secondary
Z_s = secondary impedance
Z_L = load impedance
θ = coupling angle to secondary

Coefficients of coupling vary as sine and cosine of θ to the respective output windings. ∴ Coupled secondary impedance $= X^2_m/(Z_s + Z_L) =$ constant. Similarly for a low impedance primary excitation source, the output impedance is constant.

Fig 8.2 Impedance characteristics of the electrical resolver. When properly applied, both input and output impedances are independent of shaft setting.

makes it possible to detect motions of the order of several seconds of arc. Many errors that arise as a result of mechanical irregularities such as eccentricity of rotor and stator, ellipticity of the critical magnetic air gap surfaces, or similar departures from ideal, may be balanced out over a small angular range by careful trimming and adjustment of scale factor. This is feasible because errors from these sources vary slowly and may be assumed constant or linearly varying over small ranges.

For small angle applications, the most serious error is shift in the axis or null point. The axis drifts as a result of changing conditions, primarily temperature. Drift of the order of one minute of arc is not uncommon. Where the total angular span is of the order of several degrees, drift may be a significant portion of the overall error.

Additional angular errors resulting from slot harmonics within the resolver air gap also occur. Although by careful winding design, it is possible to reduce most air gap harmonics to zero, slot harmonics can be reduced just so far, the minimum error depending roughly on the inverse square of the number of slots. In small resolvers with few slots, these harmonics may introduce as much as a minute or two of error with consequent angular inaccuracy. Scale factor or output voltage per unit displacement may vary, introducing additional error.

While scale factor may be trimmed to an exact value for a given set of operating conditions, variations in temperature, line frequency, and to some extent input voltage, will cause changes. Temperature errors, the most troublesome, are frequently compensated by the use of thermistors. In many instances, although not particularly in transducer applications, booster amplifiers employing feedback compensation are used to maintain constant input-output phase shift and scale factor over varying conditions.

A particularly troublesome source of error for small angular ranges is residual voltage, occuring in all electromagnetic components. Residual voltage appears at the null position and determines the maximum gain to which the control amplifiers may be set without saturation. Residual voltage includes both fundamental and harmonic components. Various circuits have been devised to cancel out the former. Harmonics are minimized by selecting optimum magnetic materials, operating these at very low flux densities, and maintaining large air gaps. Filtering provides further attenuation but attention must be given to avoid time delays which can affect system stability.

Table I summarizes the errors that can occur in electrical resolvers. These are typical of errors found in all magnetic-type pick-offs. This classification of errors is re-

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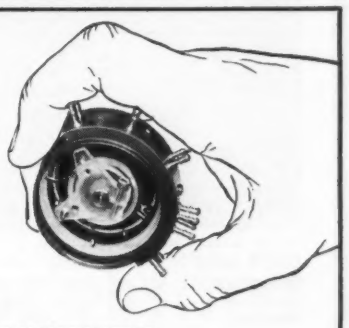

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quired to prepare an accurate specification by avoiding over-specifying certain aspects of performance while ignoring others. For example, note from the table the effect of varying input voltage on the transmission ratio of the resolver. This varying input voltage varies magnetic core permeability and consequently the main coupling reactance, changing the resolver transmission ratio. While booster compensation can correct this, boosters are bulky and expensive and introduce considerable circuit complexity. However, other methods of resolver compensation cannot correct this particular error.

TABLE 8.1

Misalignment of axes of coils, due to imperfect geometry
Slowly varying errors, due to imperfect geometry.
Variation of transmission ratio with applied voltage, see Fig. 8.3.
Temperature errors, primary copper resistance, see Fig. 4.2.
Frequency errors, transmission ratio and phase, as with any transformer.
Angular inaccuracy, resulting from imperfect sinusoidality of windings.
Application errors, due to unbalanced or non-standard loading, primary impedance unbalance, pick-up, etc.

Fig. 8.3 shows the variation in transmission ratio as a function of applied voltage for a typical resolver. At very low input voltage where the magnetic material permeability approaches its initial value, transmission ratio variation is most pronounced. At the high voltage extreme, saturation sets the operative limit. By restricting voltage range and using very high permeability alloys, such as Supermalloy, it is possible to hold these errors to acceptable limits. Where transducers operate at essentially constant voltage, this problem does not exist.

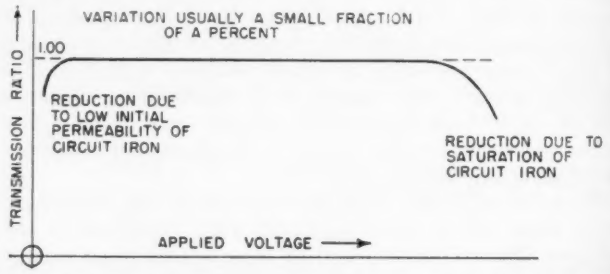
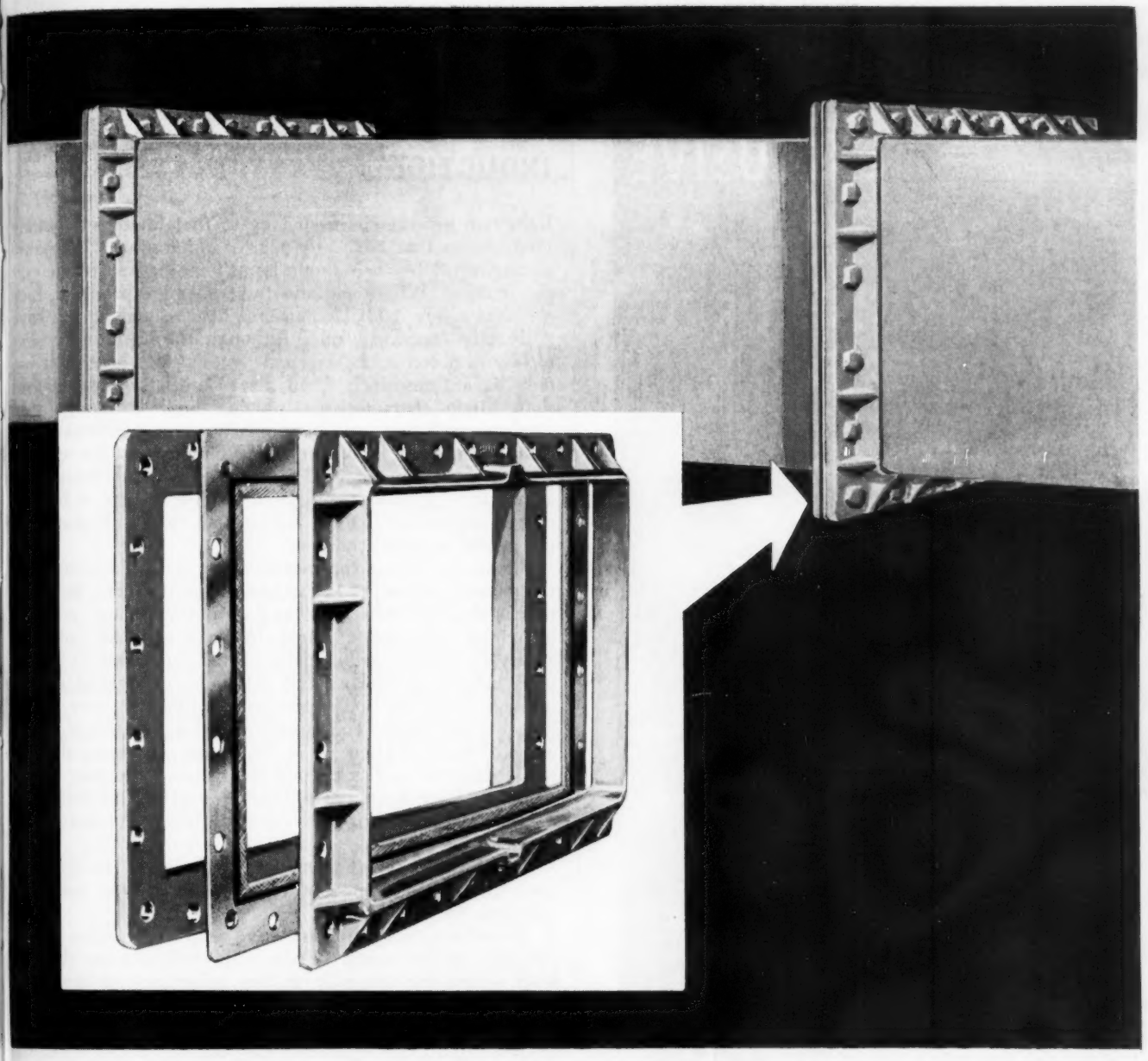

VARIATION USUALLY A SMALL FRACTION OF A PERCENT
1.00
TRANSMISSION RATIO
REDUCTION DUE TO LOW INITIAL PERMEABILITY OF CIRCUIT IRON
REDUCTION DUE TO SATURATION OF CIRCUIT IRON
APPLIED VOLTAGE

Fig 8.3 Variation of transmission ratio with applied voltage, as a result of iron nonlinearity.

Note that the resolver has an error unique to itself, namely the alignment of the axes of the different coils. These axes should be precisely 90 degrees apart. Achievement of an exact 90 degrees is very difficult. Auxiliary trimming coils have been used with some success. Axis alignment is affected by line voltage variations as the changing magnetic core permeability causes a corresponding though small shift in the flux axis. Because axis alignment is difficult to control, and because not all resolver applications require four active coils, it is often economical to classify production resolvers in accordance with the number of properly aligned windings. Thus, a grade A resolver might have excellent alignment while a grade C would have poorer alignment of axes. Grade C units might be used where only one input and one output winding are required, so that axis misalignment causes no deterioration whatever in quality of performance. This is strictly for economy, and complicates stocking of spare parts.



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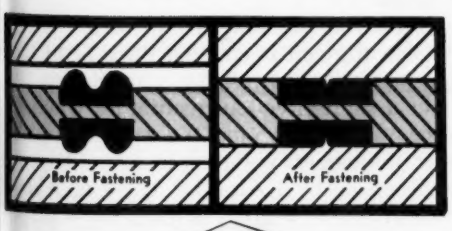

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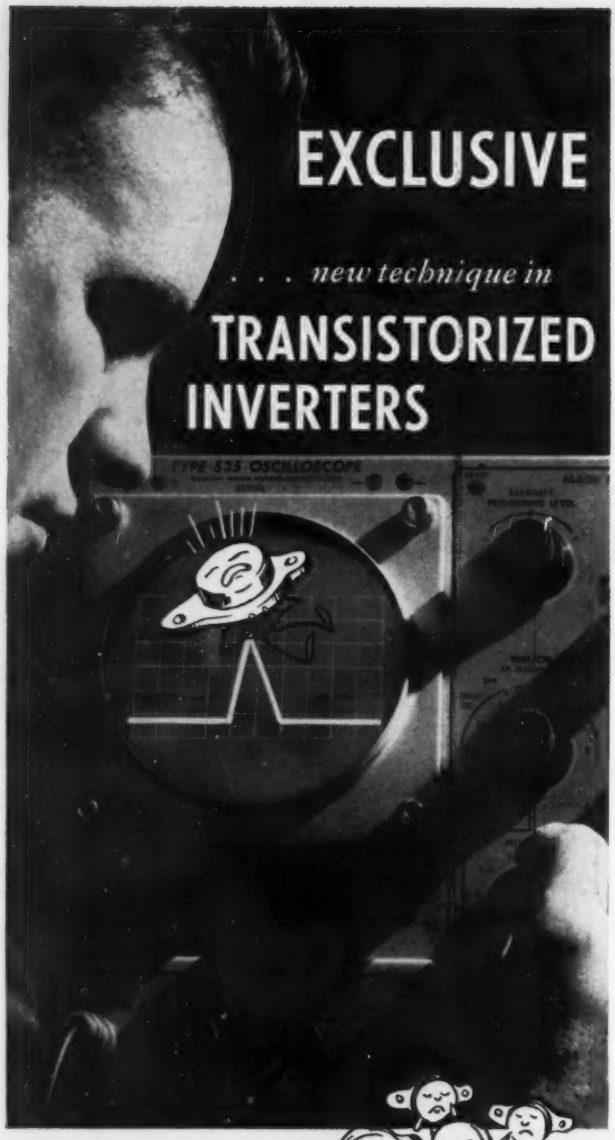

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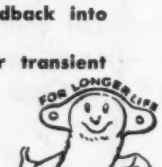

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INDUCTION POTENTIOMETERS

Induction potentiometers belong to that family of rotating components that include synchros and resolvers. They are distinguished by their single input winding and single output winding. Where additional windings are provided, they are used solely for balancing impedances, and do not have a directly functional role. Although they are used principally as a computing element, we consider here their use only as a transducer. Their linear output voltage versus shaft angle characteristics provide high accuracy, good stepless resolution, and particularly good performance in comparison with conventional potentiometers for equivalent diameters and angles of rotation. An important characteristic of the induction potentiometer to note is that its output impedance is not constant with the result that loading affects angular accuracy.

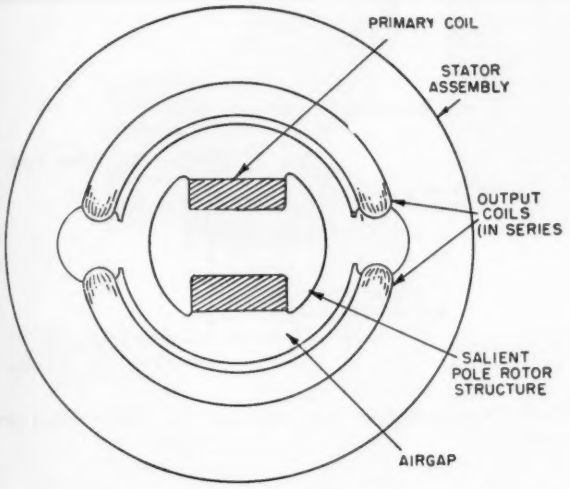
Figure 9.1 shows the performance of the induction potentiometer indicating the nature of the magnetic field, the relationship between input and output windings, and one technique whereby a linear function of shaft angle is achieved. Other combinations of windings, not described here, achieve a similar result. Although capable of infinite rotation, the induction potentiometer operates over a limited angular range. The circuit shown in the figure covers a useful angle of about 60 or 70 degrees. Accuracy deteriorates badly for angles beyond this value. Induction potentiometers have been devised with operating angles up to double this figure but they exhibit other performance limitations.

To illustrate more specialized techniques required for good performance in transducers of this type note the following in Fig. 9.2.

- To achieve a square flux wave a special booster coil is provided in the center of the main coil to raise the flux level where the normally greater reluctance of the magnetic path tends to produce a dip in flux density.
- A pair of balanced secondary windings is provided 90 degrees apart. By symmetrically loading these windings even when only one output is required, the primary impedance becomes far less sensitive to loading with greatly reduced linearity error from this source.
- A symmetrical second winding is provided on the primary structure 90 degrees from the input winding. This winding is normally short-circuited providing some of the benefits described below.

With a single primary coil, the output impedance varies from a minimum, when the coil is coupled directly to the output winding for maximum output, to a maximum 90 degrees away. Use of a short-circuited quadrature winding minimizes impedance variation so that the output impedance is a maximum at 45 degrees. Variation in output impedance is reduced by this means by 3, 4, or 5 to 1. Where a limited angular travel of about 45 degrees is required, a properly distributed winding at 90 degrees to the main winding, distributed approximately sinusoidally, results in an output impedance independent of shaft position.

An additional benefit of the shorted quadrature windings on the primary structure (both in the induction potentiometer and the resolver) besides maintaining output impedance constant, is the reduction in flux axis shaft due to housing distortion, mechanical dissymmetry, temperature changes and aging. The shorted quadrature winding cancels quadrature flux resulting from dissymmetry by generating flux bucking currents.



The airgap flux is distributed uniformly in the salient region of the rotor structure. Thus, in the position shown, the primary to secondary coupling will vary linearly with rotor shaft position.

Fig 9.1 Relationship between windings and magnetic field in an induction potentiometer, to generate a linear voltage-displacement characteristic.

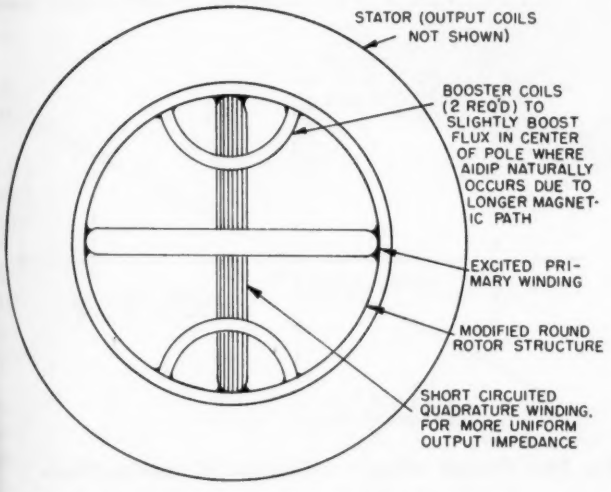

STATOR (OUTPUT COILS NOT SHOWN)
BOOSTER COILS (2 REQ'D) TO SLIGHTLY BOOST FLUX IN CENTER OF POLE WHERE AIDIP NATURALLY OCCURS DUE TO LONGER MAGNETIC PATH
EXCITED PRIMARY WINDING
MODIFIED ROUND ROTOR STRUCTURE
SHORT CIRCUITED QUADRATURE WINDING, FOR MORE UNIFORM OUTPUT IMPEDANCE

Fig 9.2 More complex induction potentiometer circuit, showing refinements required for good performance.

Application of the induction potentiometer is very similar to application of the resolver as a transducer, except that here, as a result of the linearity characteristics, a much wider angular range can be covered. Induction potentiometers possess long life, very low noise, a stepless output and can operate at very high speeds. Very important application in the computing field is not covered here since we are confining our topic to transducer applications. As with resolvers, the effect of changing air-gap reluctance, as a result of iron permeability variations with temperature or flux level, the effect of frequency shift, temperature effects on the copper winding, etc. are very similar to those previously discussed. Thermistor compensation is a convenient method for correcting temperature errors in induction potentiometers.

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DIFFERENTIAL TRANSFORMER

The differential transformer is an electromechanical transducer that generates an output voltage proportional to the displacement of a movable core. Fig. 10.1 shows the construction. The cylindrical magnetic core displaced axially establishes the flux paths and the output coupling. Fig. 10.2 is a schematic representation.

When the primary is energized with a-c, voltages are induced in the two outer coils. These coils are connected in series opposition so that the voltages in the secondary circuit cancel. At null the output voltage approaches zero.

When the core is displaced from null, the voltage induced in the coil toward which the core is moved increases, while the voltage induced in the opposite coil decreases, resulting in a differential voltage output from the transformer which can be designed to vary linearly with core motion. A phase reversal in output occurs in passing through the null. Fig. 10.3 shows output voltage vs displacement, with phase reversal indicated by voltage polarity.

Actually, due to residual voltages, output does not become zero but approaches a minimum.

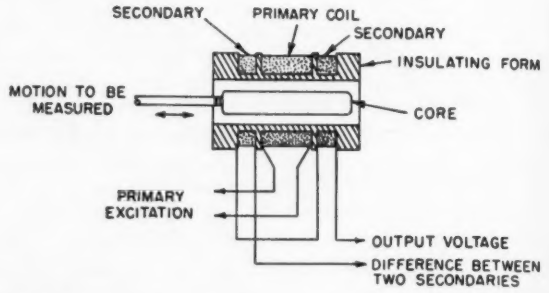


Fig 10.1 Construction features of the differential transformer.

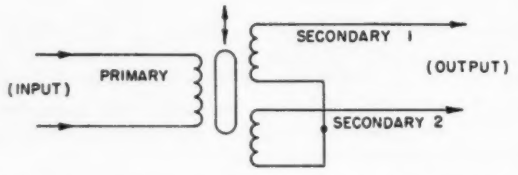


Fig 10.2 Schematic representation of the differential transformer.

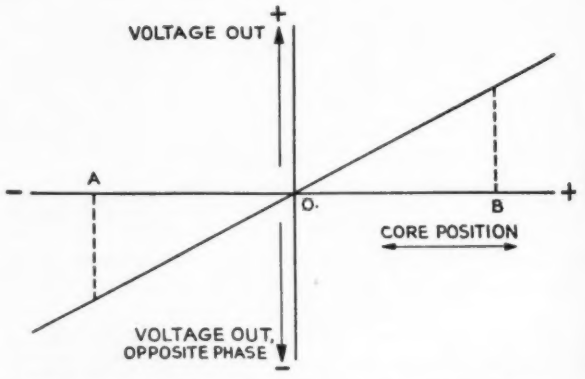


Fig 10.3 Output voltage as function of core position.

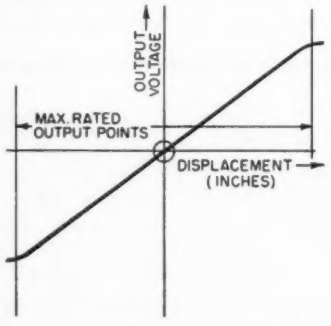


Fig 10.4 Linearity Characteristic of differential transformer. Nonlinearity is taken as the maximum deviation of the output characteristic from the best straight line fitted within the region of the maximum rated output points. Deviation is expressed as a percent of output at those points.

The Rotary Variable Differential Transformer

Schaevitz describes a rotary differential transformer developed from the basic linear type:

"Instead of the straight cylindrical core, a special 'cam-shaped' core is used; instead of being displaced along the coil axis, this special core is rotated about a perpendicular axis at the center of the usual coaxial coil assembly. The projected position of this eccentric core advances and recedes along the coil axis as the core is rotated, producing a magnetic effect equivalent to the linear displacement of a straight core. With a carefully developed core shape this arrangement produces a voltage output linearly proportional to the angle of rotation of the core over a relatively large angular range."

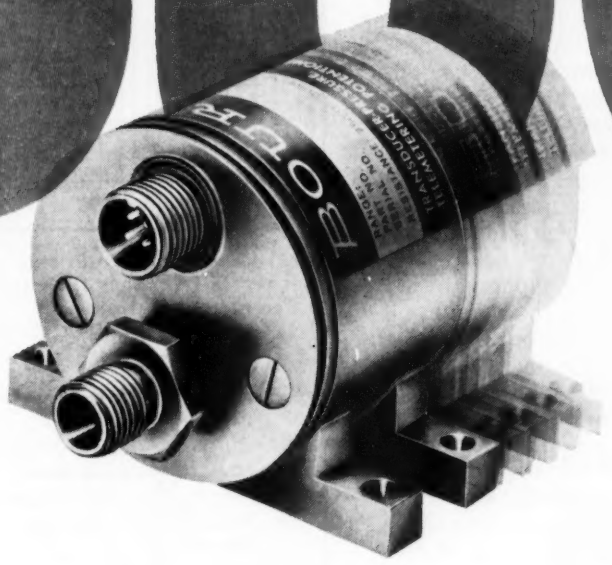
Differential Transformer Characteristics

The output voltage of a differential transformer is a linear function of core displacement within a limited range. Beyond this range the characteristic starts to curve. Linearity is usually defined as the maximum deviation of the output characteristic from the best straight line expressed as a percentage of the output at the maximum rated output point; see Fig. 10.4

Linearity and the linear range are usually specified for a given resistive load. Because output impedance is relatively constant, substantial output loading will not seriously affect linearity, although it will modify sensitivity and phase shift.

The differential transformer is similar to an ordinary transformer in many of its output characteristics. At low frequencies its output impedance is approximately resistive, while at higher frequencies it may assume high reactive values. As a result, at high frequencies, the output sensitivity (volts output per inch displacement) may diminish rapidly. Similar input impedance will go up with increasing frequency. The frequency characteristic of a typical unit is shown in Fig. 10.5. Where the differential transformer is required as a signal device in a control or measurement application, very light loading gives the best performance. At times however, it may be advantageous to draw power

35G



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from the unit, as for example, to drive a relay. In accordance with conventional circuit theory, maximum power transfer occurs when the load (relay) impedance approximately equals the differential transformer output impedance. To achieve this match the impedance either of the load or of the differential transformer may be properly adjusted or a matching transformer may be inserted between them. Schaevitz indicates that a rectifier may be used in the output load circuit where d-c is required. Matching is generally not critical.

APPLICATION NOTES

Many of the application factors discussed elsewhere apply to the differential transformer. Output voltage sensitivity may be increased by increasing primary voltage. At very low and very high primary voltages the permeability of the magnetic circuit diminishes sharply, with a reduction in the output to input voltage ratio. Within the broad intermediate band, this ratio is approximately constant. Similarly, once saturation sets in at the higher input voltages, the harmonic distortion in the output increases rapidly. More input voltage is required for saturation at higher frequencies. Power input and heating increase as the square of the applied voltage. Units required to deliver power to a load operate at relatively high power levels. Because of the high magnetic circuit reluctance, heating rather than saturation usually limits the input power. A loading capacitor will frequently increase the output voltage, reduce distortion and at the same time bring the basic phase shift to zero, all frequently desirable objectives. However, such tuning should be evaluated experimentally for adverse effects on performance if frequency is to be varied.

Internal heating as well as ordinary variations in ambient temperature introduce variations in sensitivity due to changes in resistance of the primary winding. At low frequencies, resistance changes affect the output magnitude, while at very high frequencies principally phase shift is affected. Sometimes constant current excitation on the primary is desirable to eliminate output variation due to primary resistance changes with temperature. Winding the primary with a very low temperature coefficient wire, such as Manganin, will yield a similar result but at considerably reduced sensitivity due to the high resistivity (and consequent heating to be expected) with that material.

The differential transformer impedance relationships may be analyzed in accordance with the circuit equations previously presented. Generally speaking, the output of a differential transformer is leading in phase shift, the angle of lead increasing for smaller units and at lower frequency. Load resistance tends to bring a leading phase angle back toward zero. At low frequencies however, where the output impedance is largely resistance, the load resistance required for zero phase shift becomes very low, with a consequent large attenuation in output sensitivity. At higher frequencies, load resistance is a very convenient means for trimming phase-shift to zero. As frequency increases, phase shifts from 90 degrees leading to 90 degrees lagging as for any conventional transformer. Fig. 10.6 shows some of the circuit connections recommended by Schaevitz for bringing phase shift to zero.

NULL VOLTAGES

The null voltage of the differential transformer, where the position sensitive component of the output voltage is zero, consists of fundamental frequency as well as harmonic

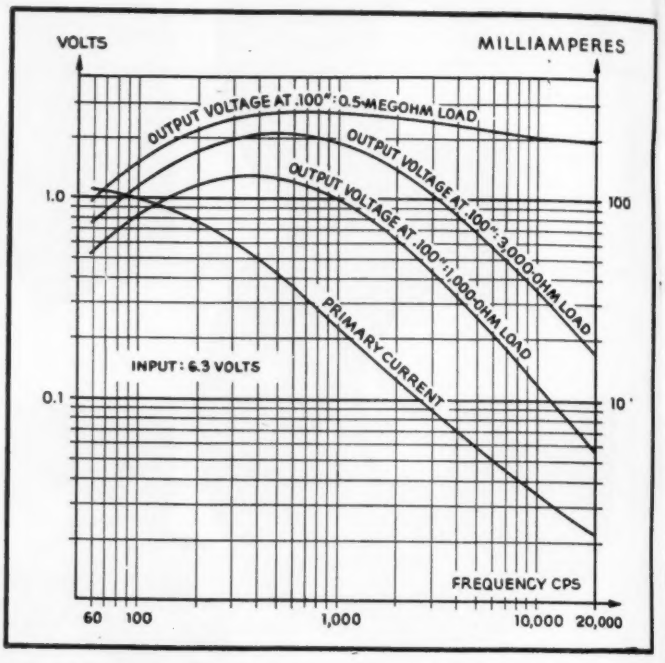


Fig 10.5 Nominal full-range output volts and primary current versus frequency for a typical Schaevitz Linear Variable Differential transformer.

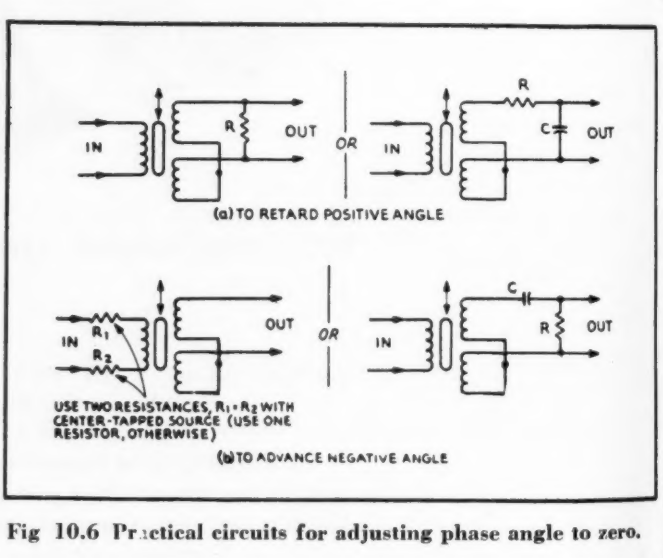


Fig 10.6 Practical circuits for adjusting phase angle to zero.

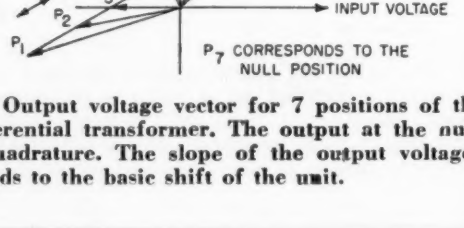
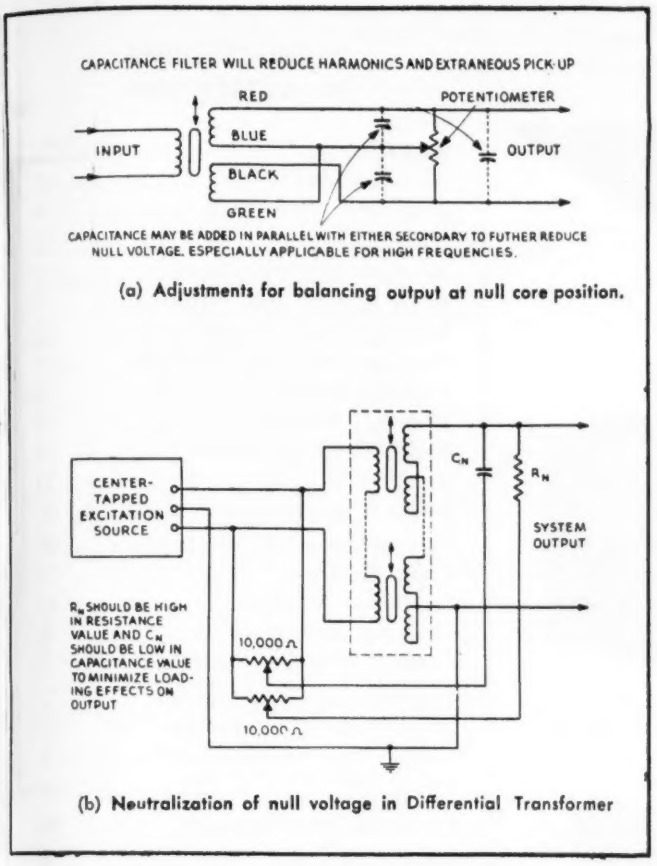


Fig 10.7 Output voltage vector for 7 positions of the core of a differential transformer. The output at the null position is quadrature. The slope of the output voltage locus corresponds to the basic shift of the unit.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OUTPUT
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(a) Adjustments for balancing output at null core position.
CENTER-TAPPED EXCITATION SOURCE
C_N
R_N
SYSTEM OUTPUT
R_N SHOULD BE HIGH IN RESISTANCE VALUE AND C_N SHOULD BE LOW IN CAPACITANCE VALUE TO MINIMIZE LOADING EFFECTS ON OUTPUT
10,000Ω
10,000Ω
(b) Neutralization of null voltage in Differential Transformer

Fig 10.8 Circuits for reduction of null voltage.

components. The harmonics, resulting from the nonlinear characteristics of the magnetic material, are kept to tolerable limits by operation at relatively low flux densities. Fundamental components of the null however, resulting from dissymmetries in geometry and material properties, are controlled by careful engineering and manufacture, and, where required, by some simple trimming procedures.

The fundamental null voltage itself may be resolved into two vector components, one in time phase with the displacement sensitive output and the other in time quadrature. The former in effect corresponds to a slight shift in null position, and as a consequence has trivial significance. That is, the setting of the best zero position for the differential transformer in effect cancels out any "in-phase" component of null. For all practical purposes, the fundamental null voltage is in time quadrature with the displacement sensitive voltage, and is referred to as *quadrature*. Fig. 10.7 shows the variation in fundamental output voltage of a differential transformer versus displacement, indicating how the output passes through a minimum rather than zero, because of the presence of quadrature.

Since stray capacitance is a factor in generation of null voltages, it is important to pay attention to proper grounding. The null of a differential transformer designed for phase applications must be defined in terms of a particular circuit configuration and grounding conventions. Frequently a balanced excitation source with grounded center-tap, with one (specified) secondary lead returned to the same ground point, provides desired performance.

Fig. 10.8 shows some circuits recommended by Schaevitz for balancing out quadrature for individual units, and for a pair operating together. It is not good practice to use trimming procedures to cancel out large null voltages resulting from poor wiring practice, stray fields, or the presence of large masses of metal that serve to distort the differential transformer flux fields.

MISCELLANEOUS CONSIDERATIONS

The behavior of the differential transformer may be modified somewhat by selection of "optimum" core length. Optimum core length is a function of linear range, sensitivity and frequency. A shorter core may produce increased sensitivity at the expense of linear range. Length and weight of the core may sometimes be restricted by application requirements.

Axial and radial forces act on the magnetic core but in most instances, with care in installation, the effects are negligible. Axial force varies approximately linearly with displacement of the core from the null position. Radial forces increase as the core is displaced from a perfectly centered position in the coil assembly. The core is in a position of unstable equilibrium since the slightest off-center motion initiates further motion toward the nearest portion of the core. The core must be maintained centrally on the transformer axis for satisfactory operation.

Radial and axial forces diminish sharply with reduction in primary current, for example, at reduced excitation level, or high frequencies.

Differential transformers are available with and without magnetic shields, in a wide variety of sizes, ratings, ranges, etc. Units can meet rigid environmental specifications where required. However, wide temperature ranges introduce phase shift and sensitivity errors, which may be compensated by thermistor networks, or other means.

This section ends the first part of Components Digest 3 —Electromagnetic and Potentiometer Transducers. As discussed more fully in the editorial, the second part will appear in March and the third part, including a buyers' guide for transducers, in May. This extension will not interfere with CD 4, "Environmental Testing", scheduled for March.

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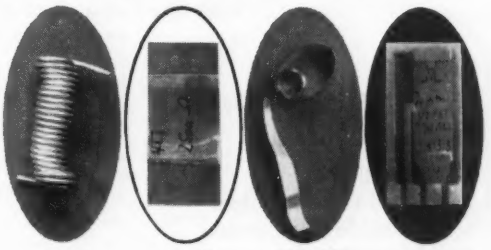

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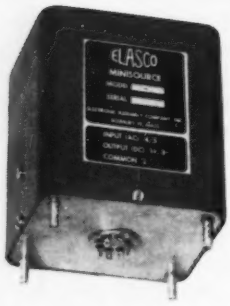

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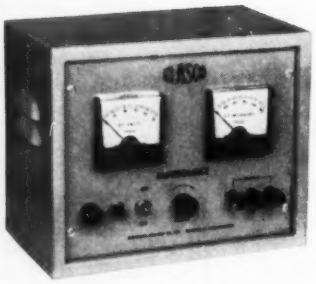

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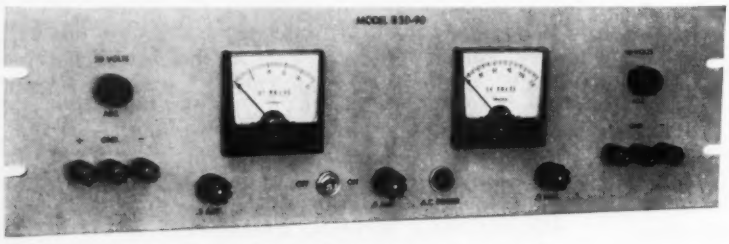

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Miniature Transformers, including miniature, subminiature, transistor and industrial transformers described in catalog with listing of complete specifications. Microtran Co., Inc., Valley Stream, New York. Circle 225.

Insulator Plastics catalog describes diallyl phthalate plastic molding materials, with a listing of advantages, including insulating qualities and dimensional stability even under severe environmental conditions. Catalog has complete property and molding data charts for dacron-filled, asbestos-filled, glass-filled and orlon-filled types, and features data on diallyl iso-phthalate molding compounds with heat resistance up to 500°F. Properties of each type of molding compound are compared in master chart. Mesa Plastics Co., Los Angeles, Calif. Circle 239.

Bridge-Meg Tester is insulation tester and wheatstone bridge in one portable instrument. A complete resistance measuring set with power supply, the unit has a range from a fraction of an ohm to 1000 megohms. James G. Biddle Co., Phila., Pa. Circle 234.

Varactor is a diffused silicon PN junction diode designed to be a variable capacitance with low loss at high frequencies. Useful in low-noise diode amplifiers, amplifying up-converters, harmonic generators, high-level modulators, frequency dividers, voltage-variable tuners, switches, reactive limiters, and high-speed computers, the unit complies with MIL-E-1 outline 7-1 for cartridge type crystal rectifiers and will fit most standard crystal holders. Harmonics have been generated as high as 100 kMc. Microwave Associates, Inc., Burlington, Massachusetts. Circle 179.

Magnetic Amplifiers and saturable reactors including associated circuitry and equipment, described in booklet along with advantages of magnetic amplifiers and the reliability, maintainability and applications for magnetic amplifier equipment. Brach Mfg. Corp., Newark, N.J. Circle 191.

Digital Volt-Ohmeter bulletin describes theory of operation of new precision digital VTVM and lists pertinent characteristics in detailed specification table. Franklin Electronics, Inc., Bridgeport, Pa. Circle 157.

Angularly Adjustable Coupling designed to provide precision rotational angular adjustment between two synchro rotors or other mechanisms requiring angular displacement, achieves its purpose by turn of the coupling adjusting screw. One turn rotates one coupled shaft in respect to the other through only 12 degrees. Continuous rotational adjustment through 360 degrees in either direction is another feature of this coupling. Adjustment can be locked at any desired setting. Overall length: 1.862 inches; overall diameter: 51/64 inches. PIC Design Corp., East Rockaway, L.I., New York. Circle 237.

Fiber Research Literature lists on electron microscope work and X-ray diffraction investigations reference papers which appeared in domestic and foreign publications, textbooks and reference books. Philips Electronics, Inc., Mount Vernon, N.Y. Circle 215.

AC Linear Accelerometer consists of a non-pendulous seismic mass supported on a frictionless spring suspension and incorporates an a-c variable reluctance type pick-off. Inherently insensitive to cross-coupling accelerations both when at null and when under an acceleration along its sensitive axis, the unit also features magnetic damping for near-constant damping ratio from −65F to +250F. The accelerometer is hermetically sealed, requires no warm-up time. Mechanical stops prevent damage from input accelerations. Minneapolis-Honeywell, Boston Division, Boston, Mass. Circle 172.

Electromechanical Actuator glossary, 8 pages, is offered to promote better understanding of the design parameter of these units and what they can do. Hoover Electric Co., Columbus, Ohio. Circle 240.

Magnetic Amplifiers bulletin contains brief technical discussion of basic magnetic amplifier theory, circuitry and applications. Entitled "Techni-Topics", it is published regularly by technical staff as application notes on company's products. Magnetic Controls Co., Minn., Minn. Circle 235.

Light Weight 1.0 HP Motor is 4 inches long, 2½ inches in diameter, 2¾ pounds, in weight. This 22,000 rpm, 400 cycle, 208 volt, 3 phase a-c motor is suited for missile applications. Its shaft configuration is ¼ inch diameter by ½ inch length, slotted by ¼ by 1/16 inch Woodruff Key. Hoover Electric Co., Columbus, Ohio. Circle 236.

Osciducer, an ultra miniature pressure-to-frequency converter which provides a new simplified approach to FM-FM telemetering, consists of a stabilized silicon transistor oscillator wedded to a variable inductance diaphragm-type pressure transducer to provide a complete in-line instrumentation module for the remote measurement of pressure. Commonly used interwiring between oscillator and transducer has been eliminated. The unit requires only three connections for operation: 28 volts DC at 2 milliamperes, ground and the output and silicon transistor emitter follower low-impedance output is provided to isolate the oscillator from external loading. Solid State Electronics Co., Van Nuys, Cal. Circle 155.

Electron Tubes: klystrons, magnetrons, photomultipliers, cathode ray tubes, storage tubes, secondary emission pentodes, vidicons, orthicons, and other special purpose electronic tubes by EMI Electronics, Ltd., described in two new catalogues. These catalogues contain complete technical information relating to application, performance, mechanical construction, sizes, and weights. H. L. Hoffman & Co., Inc., Westbury, L. I., N. Y. Circle 197.

Pressure Switches are described in brochure, listing four basic types: absolute, gage, differential and thermal pressure switches, along with factors determining their selection, including vibration and shock, temperature, altitude and atmospheric conditions. Brochure discusses applications and suggests new uses. Gorn Electric Co., Inc., Stamford, Conn. Circle 224.

Gearshift Drive construction and typical applications described in bulletin, showing original equipment photos and giving comparative data between "selective-speed" gearshift and other types of drives. The Lima Electric Motor Co., Inc., Lima, Ohio. Circle 217.

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